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FINAL REPORT

ON

METALLIZED KEVLAR SPACE TETHER SYSTEM
(CONTRACT NAS8-37256)

TO

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C. MARSHALL SPACE FLIGHT CENTER
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FROM

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PREFACE

This report summarizes work performed by Material Concepts, Inc. (MCI) on a Phase II SBIR Program sponsored by the National Aeronautics and Space Administration (NASA)-Marshall Space Flight Center under Contract NAS8-37256. The program was performed over the two-year period from May 22, 1986 through May 21, 1988. The NASA-Marshall Contracting Officer's Technical Representative (COTR) for this program was Mr. Fred Wills. The Program Director and Principal Investigator at MCI was Ralph F. Orban with technical support provided by Messrs. Tom Smith, Keith Miller, and Robert Francini.

The author gratefully acknowledges the additional guidance and support of Messrs. James K. Harrison and Chris C. Rupp at the Advanced Projects Office of NASA-Marshall. A special acknowledgement is extended to Dr. Alan Koralek of DuPont for his constant source of technical information on Kevlar products and testing performed by DuPont, and Mr. John Bednarczyk, also of DuPont, who performed the polymeric coating of metallized Kevlar for this program. A special acknowledgement is also extended to Mr. Norman Randall at Fiber Materials, Inc. for all his help in preparing the prototype space tether constructions, Dr. Paul Ibanez and Mr. Alejandro Levi of Anco Engineers, Inc., Culver City, CA, for the tether damping studies, and Mr. Dewitt Burns, Physical Sciences Branch, NASA-Marshall, for the series of simulated atomic oxygen tether exposures.

SUMMARY

The objectives of this program were to refine the process used to metal coat Kelvar (polyaramid) and to use this material in several electrically conductive, prototype space tether systems. In addition to describing the basic processing, several problem areas are discussed including batch versus continuous processing and how to restart the daily process without leaving uncoated fiber between runs.

Testing of several preliminary and final space tether constructions includes break-load and electrical conductivity data, and results of a preliminary damping study.

Future work should concentrate on developing the capability to produce the quantities of metal-coated fiber required for tether applications, actual space exposures to access the impact of damage by atomic oxygen, and most importantly, the development of high temperature fiber/coating combinations which could be used at low earth orbit applications for atmospheric investigations.

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INTRODUCTION

Background

The original work in this area began with a Phase I NASA SBIR program in December 1984 which proposed metal coating the DuPont polyaramid "Kevlar" for use in an electromechanical space tether system.* Prior to this work, prototype space tethers consisted of two components: a strength member, which was some form of synthetic fiber (usually Kevlar)**, and a conductive member (a copper wire embedded inside the strength member). Because the dissimilarity of the two components presented some engineering difficulties, the idea of metal coating the Kevlar strength member and, thus, combining the two members into one was conceived. During this early Phase I work, a Pilot Fiber Coating Line was designed and built to metal coat fiber continuously. Various metal coatings were deposited on pilot quantities of Kevlar and tested. The optimum material was Kevlar 49, which was coated with one micron of copper plus a light nickel overcoat to prevent the copper from oxidizing. Testing involved electrical resistance measurements, SEM examination, and exposure to an oxygen plasma to simulate exposure to atomic oxygen.

Objectives

The primary objectives of the Phase II program were as follows:

1. To metal coat multifilament Kevlar tows and to test and valuate them both before and after environmental exposure.

2. To improve quality control, metal coating thickness and deposition rate of the metal coating process.

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* Metallized Kevlar Space Tether System, Phase I Final Report, NASA-Marshall, July 12, 1985.

**Note that Kevlar is the DuPont Company's registered trademark for its aramid fiber.

3. To develop specifications for both a finished tether system and for the metal-coating processing.

4. To investigate the use of polymeric insulating coatings.

5. To produce a 2.5 kilometer braided, conductive sample space tether.

Since there was no specific mission planned for this material, the last objective was altered midway through the program: "To produce braided, conductive space tethers of varied constructions".

Experimental Work

As originally envisioned, work on this program was organized into the following tasks.

Task 1: Production of metal coated Kevlar samples using the improved techniques developed toward the end of the Phase I effort. Also included would be a brief investigation of coating Kevlar with gold. Samples produced during this work would also be subjected to a space exposure.

Task 2: Examination and testing of samples prepared and exposed during Task 1. Specific areas of investigation would include measurement of electrical conductivity, tensile strength, mass loss, and coating thickness, uniformity, and integrity. Also to be addressed would be an improved method of determining electrical conductivity and outgassing experiments.

Task 3: Improvement in quality control of the MCI proprietary metal coating process. Potential monitoring areas to maintain quality include electrical resistance, weight per unit length of coated material, and visual/microscopic examination. The use of

automatic chemical analysis and addition units would be investigated along with the increase of capacity of the Pilot Fiber Coating Line designed under Phase I.

Task 4: Improving and/or increasing metal-coating thickness, rate, and quality. Several new and improved metal-coating methods would be employed. Insulating polymers would also be investigated, and studies would be performed to determine the relationship between metal-coating thickness and tensile strength/conductivity.

Task 5: Prepare a large quantity of metal-coated Kevlar based upon previous work conducted in Tasks 1 to 4. This optimum material would then be used in Tasks 6 and 7.

Task 6: Optimization of a finished sample tether. Several construction methods would be investigated including braiding, axial braiding, and combinations of both. Also, short sample tethers capable of carrying various payloads and possessing varying electrical resistance would be constructed, subjected to oxygen plasma exposure, and tested. Strength, electrical conductance, and polymer insulating capability versus mass and volume would also be addressed to optimize the tether system. Both electrical and mechanical termination techniques would be investigated along with splicing and repair techniques.

Task 7: Prepare a small sample tether for space exposure. After exposure, extent and depth of damage would be assessed.

Task 8: Preparation of specifications for both a finished production space tether and for the contractor's production processes: metal coating, polymeric coating, construction, quality control, and testing.

Task 9: Production of a 2.5 kilometer conductive space tether to be used on a specific shuttle mission. The tether would be capable of conducting a 10,000 volt current at 0.1 amp and supporting a tension load of 0.5 Newton. During this task, all specifications developed in Task 8 would be followed.

Task 10: Preparation of the Final Report

Changes to this plan were made throughout the program to conform to new objectives which arose over the two year period. Due to the Challenger Space Shuttle disaster, all plans for actual exposures of tether samples in space had to be abandoned. (Note: Preliminary tether samples for space exposure had been submitted to NASA after the close of the Phase I program and were scheduled for launch in the Fall of 1986. It was also planned to use data gathered from this exposure for the subject program.)

PROCESSING OF METAL-COATED KEVLAR

Background

The continuous processes for metal coating various synthetic nonconductive fibers were developed at MCI and involve a duplex (or two step) process (Figure 1). In the first step, the fiber is specially treated with a catalytic activation; an autocatalytic metal coating process is then used to render the fiber electrically conductive. If a heavier deposit of metal is required, then a second electrodeposition step is used. The basic process for metal coating polyaramid (DuPont's Kevlar) is covered under U.S. Patent No. 4,634,805 and was briefly described in NASA Tech Briefs, Volume 12, No. 2, pp. 18-21 (February 1988)(see Figure 2).

At the close of the Phase I NASA program the most promising material was a duplex coating of copper with an overcoat of nickel to retard oxidation. Electrical resistances on the order of 1 ohm per foot (3 ohms/meter) were achieved when processing a single line of fiber. Typical runs of a few hundred feet per day were possible. However, several problems seemed to be inherent in the processing. For example, certain runs of the same type of Kevlar seemed to coat better than others. It was easier to coat Kevlar 49 with copper and Kevlar 29 with nickel, but harder to coat copper on Kevlar 29 and nickel on Kevlar 49. And, every so often, a bare spot, which could run from a few inches to a few feet, would show up for no explainable reason.

The Phase I program did show the feasibility of and potential for using metal-coated Kevlar (polyaramid) in a space tether system. However, many areas needed to be further investigated during a Phase I effort:

- Can the processing rate be increased by using new chemical processing solutions?

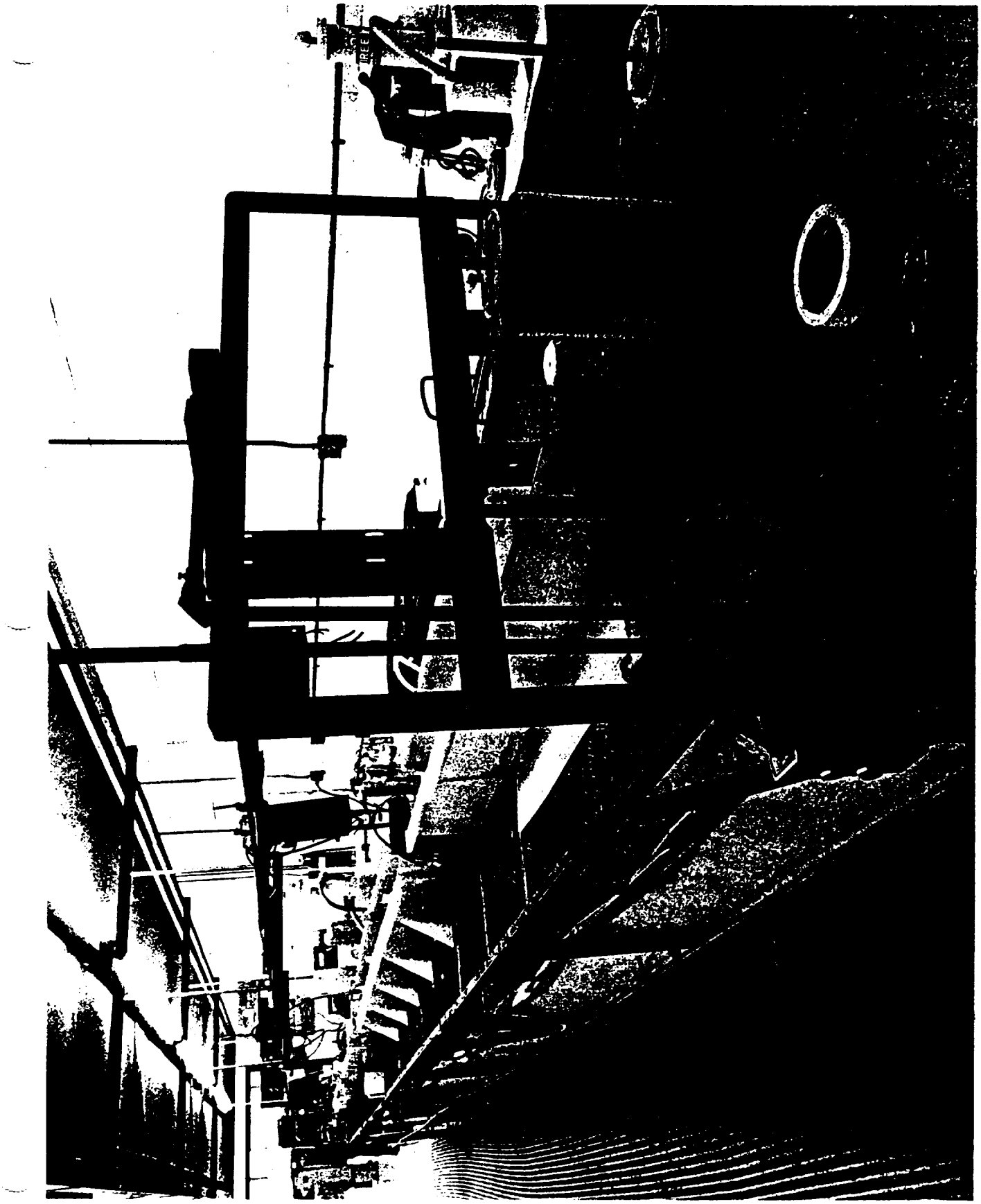

FIGURE 1. PILOT FIBER COATING LINE IN OPERATION

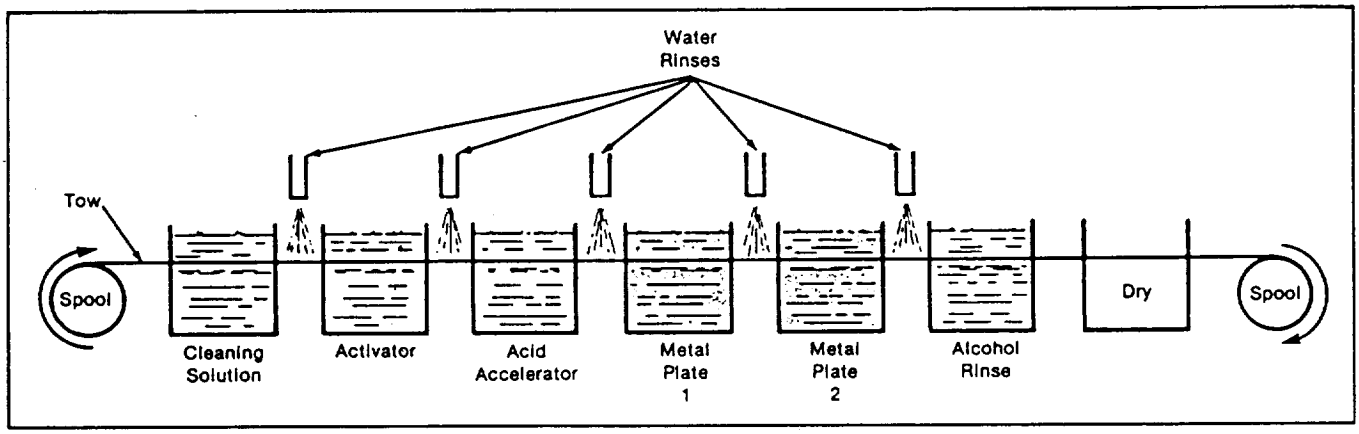

FIGURE 2. PROCESSING SEQUENCE FOR POLYARAMID TOWS

- Is there any way to eliminate the bare uncoated spots which would appear during processing?

- Can the processing be restarted without uncoated material appearing between runs?

- Can multiple lines be processed simultaneously?

- Are commercial units available which can be used to continuously process material?

- What equipment is available to monitor the quality of the material produced and the processing solutions during operation?

Process Chemistry

As was mentioned earlier, the MCI proprietary metal coating process deposits metal in two steps, the first being an autocatalytic process. Several commercial autocatalytic copper solutions are available, and some are advertised to be higher speed than the standard one used at MCI. The problem with many of these high-speed processing baths is that they are operated at above room temperature to increase metal deposition rate, but are generally unstable (i.e., will decompose faster than the standard room temperature baths).

A "new" high-speed copper bath which operates above room temperature but not at as high a temperature as other high-speed baths was obtained and tried. If this bath would perform as advertised, then the possibility of depositing the required amount of copper in one step instead of two would be possible.

Experiments showed that the new copper bath was more stable than the higher temperature baths but still not as stable as the

room temperature baths. Further, the increase in deposition rate was not significant enough to reduce the two-step process to one-step.

A second avenue addressed was use of the catalytic activator which must be used on nonconductors prior to autocatalytic metal deposition; the activator is normally used in a diluted form. Various concentrations were experimented with, including use of the fully concentrated activator (i.e., no dilution); however, no improvement in deposition quality or rate was noted.

The third area of interest concerned the intermittent bare spots which could show up for no apparent reason during processing. Bare spots could run from a few inches to a few feet. In talking with technical personnel at DuPont, it was found that different sizings* were put on Kevlar 29 than on Kevlar 49. Further, a new facility was built to produce Kevlar, and, thus, processing had undergone some changes. Although both facts were potential explanations for intermittent bare spots, neither was a solution to the problem.

DuPont has a "scouring process" to remove sizing from Kevlar; however, it takes a couple of hours to process the material, and this was judged unacceptable for MCI's continuous processing system. Therefore, several organic solvents and commercial cleaners were tried to alleviate the problem. A commercial cleaner produced by MacDermid Chemical Inc. was found to solve the intermittent spot problems and it is now used as a standard step in MCI's processing. Further, the earlier problem encountered where Kevlar 29 would coat better with nickel while Kevlar 49 would coat better with copper was solved by using this MacDermid cleaner.

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*Sizings are placed on fiber to improve handleability (i.e., allows fiber to be braided and woven).

Batch Processing

In the continuous metal coating of fiber, a number of parameters must be closely controlled. It was felt that perhaps "batch processing" might offer some advantages (i.e., spool up a long length of fiber, and process the spool through each of the processing steps in a batch mode). If something went wrong with a processing solution bath, only one batch of fiber would be ruined. Further, batch processing might be faster than continuous processing with the present constraints of the pilot fiber coating line.

After several experiments, it was found that the batch mode of processing (i.e., metal coating) fiber does work, but it has several drawbacks. First, when using a 1 foot diameter reel, only about 500 feet maximum could be spooled up and processed at one time; if larger amounts were attempted, the material could not be fully activated and thus would not be fully metal coated.

To scale batch processing up to the lengths that would be required for tether applications would mean using reels so large that mechanical means would have to be employed to manipulate the reels from solution tank to tank. In addition, the batch processing would only be appropriate for the autocatalytic coating step (i.e., would have been more attractive if the high-speed copper would have worked); to obtain the amount of copper coating necessary for the space tether application would have still required the second metal deposition step. Thus, work in this area was terminated.

Process Restart

In the continuous metal-coating process, portions of the length of fiber being coated are at all the various stages of processing (catalytic activation, rinsing, metal coating, etc.)

at any one time. When the process is stopped at the end of a day, the fibers sit in the various tanks overnight. On re-starting the processing the next day, bare spots appear at various stages until a new portion of fiber is completely processed. These bare spots are due to certain portions of the fiber being exposed to rinsing for an overextended period or, in the case of fiber which is stopped between processing tanks, it is due to the fiber drying out.

A procedure was worked out so that the processing line would be restarted without the above problems. At the end of a production period, all fiber is withdrawn from the processing tanks and suspended above the tanks. Then the fiber is lightly rinsed with deionized water. On restarting the process, all fiber is again lightly rinsed with deionized water, and the entire length of fiber is "backed up" so that whatever processing step a particular piece of fiber had progressed to is repeated.

When the above procedure is carefully followed, no bare spots appear between daily "production runs" of metal-coated fiber.

Commercial Equipment

The availability of commercial equipment was explored in three areas: commercial processing units (e.g., reel-to-reel platers), quality control equipment (i.e., equipment to monitor the quantity of metal deposited and quality of metal-coated Kevlar), and process control equipment (i.e., equipment to monitor solution concentrations).

Reel-to-reel platers are commercially available and are used to metal coat wire and strips of metal. Because the MCI Pilot Production Line is very similar, two companies who produce such units were contacted. Both gave preliminary estimates of around $250,000 to build such units, and the addition of water

pollution control equipment could add up to another $150,000.00. Units would be capable of handling multiple lines (5 to 10) and would be totally automated (i.e., solution control equipment would be built into the unit). However, when questioned further, both companies failed to respond with firm quotes.

Currently, to measure the amount of metal deposited on fiber, the following procedure is followed.

1. Weigh a measured length of bare, uncoated fiber (e.g., 1 foot).

2. Weigh the same length of coated fiber.

3. Subtract the uncoated weight from the coated weight to determine the amount of metal deposited.

4. From the number of filaments in a bundle or tow, the geometry of each filament (i.e., a cylinder for Kevlar), and the metal density, calculate the amount of metal on each filament. Note that resultant metal thickness is an average for all filaments in a tow. In reality, some may be coated heavier than others.

Once the conditions on the line have been set to produce the desired metal-coating thickness as verified by the above procedure, all processing parameters are held constant until the end of the run, when another sample is cut and weighed. For continuous lengths of metal-coated fiber, it is obvious that pieces of coated fiber cannot be removed during the run. Therefore, the problem is one of how to constantly, nondestructively monitor level of coating thickness. Several commercial units are available for determining metal thickness on a conductive surface (i.e., one metal coated over another metal). However, no low-cost systems were found that could be used to measure metal coating thickness on nonconductive fiber.

To date, the only practical nondestructive measure of metal coating thickness is electrical resistance: the greater the amount of metal deposited, the lower the resistance. Once the desired level of metal is confirmed by using the procedure previously described, then the electrical resistance is measured over a specified length of coated fiber. Electrical resistance measurements are made during processing; changes in resistance are then used to adjust processing parameters.

It should also be mentioned that visual inspections of processed fiber are constantly employed during metal coating. Samples which are weighed to determine amount of coating are also checked optically with a microscope to insure uniform and consistent coverage. Examination of coated fiber bundles during the Phase I work with a scanning electronic microscope (SEM) verified that coatings were fairly uniform around the outside of each fiber.

Autocatalytic solutions deposit metal onto a substrate via a reduction reaction and their concentration of components must be kept within specified limits to perform consistently. Although standard wet methods of analysis can be used to monitor solutions and make the necessary adds (usually performed hourly), it is far better to constantly monitor solutions and make small, incremental adds. Commercial units which perform this monitoring and also make the adds are available. For small, experimental baths, their cost would not be justified. However, in a production environment with large volumes of solutions they would be worthwhile, if not absolutely necessary.

Multiple Line Processing

A logical way to increase production of metal-coated Kevlar for tether applications is to process more than one tow (or bundle) of fiber through the series of solutions at a time.

Since the autocatalytic process is time dependent, it would seem reasonable to run several lines simultaneously for the same exposure in the metal-coating bath and thus achieve the same level of coating on each bundle.

In the MCI Pilot Fiber Coating Line, several motor drives are used to transport the fiber through the series of processing steps. Each motor drive operates a set of rubber coated, tensioned rollers which are 1 inch in diameter and 8 inches long. When attempting to drive several lines through the rollers it was found that the tension varied along the length of the rollers, resulting in variations of speed for each line. Thus, certain lines had longer dwell times at various stages of the processing, which resulted in slightly heavier metal coatings. This variation was then further compounded when the lines reached the standard electroplating step. The lines which contain more metal are naturally more conductive. If common contacts are used for the fibers as they pass through the electroplating bath, the more conductive line will receive more electric current and thus deposit more metal from the bath.

To properly run multiple lines, each line will require a separate set of motor drive rollers which are synchronized so that all run at the same speed. Further, each line should have separate contact points in the electroplating bath so that the current is distributed evenly.

PROTOTYPE SPACE TETHER CONSTRUCTIONS

Introduction

One of the original objectives of this program was to produce a 2.5 kilometer braided, conductive prototype space tether using metal-coated Kevlar. However, due to the Challenger Space Shuttle disaster, such a tether would serve no real purpose at this time since it is not required for a specific mission. Therefore, several different prototypes were attempted to determine exactly what could be done with the metal-coated Kevlar material.

It should be pointed out that the prototypes in themselves are not necessarily final products, but were built to demonstrate what could be done with metal-coated fiber--in particular, Kevlar.

Preliminary Prototypes

A few basic questions had to be answered prior to preparation of actual prototype tethers, namely: can the metal-coated Kevlar be braided or woven, or will it present handling problems? If required, can an insulating polymer be placed on the metal-coated Kevlar?

To answer the latter question, Kevlar 49 (1420 denier, 1000 filaments per tow) coated with copper (Figure 3) was sent to E.I. duPont de Nemours & Co. (Wilmington, Delaware) where four prototypes (Figure 4) were prepared:

Prototype 1: 1 tow of copper coated Kevlar 49--pressure extruded with a 11 mil wall thickness of Tefzel

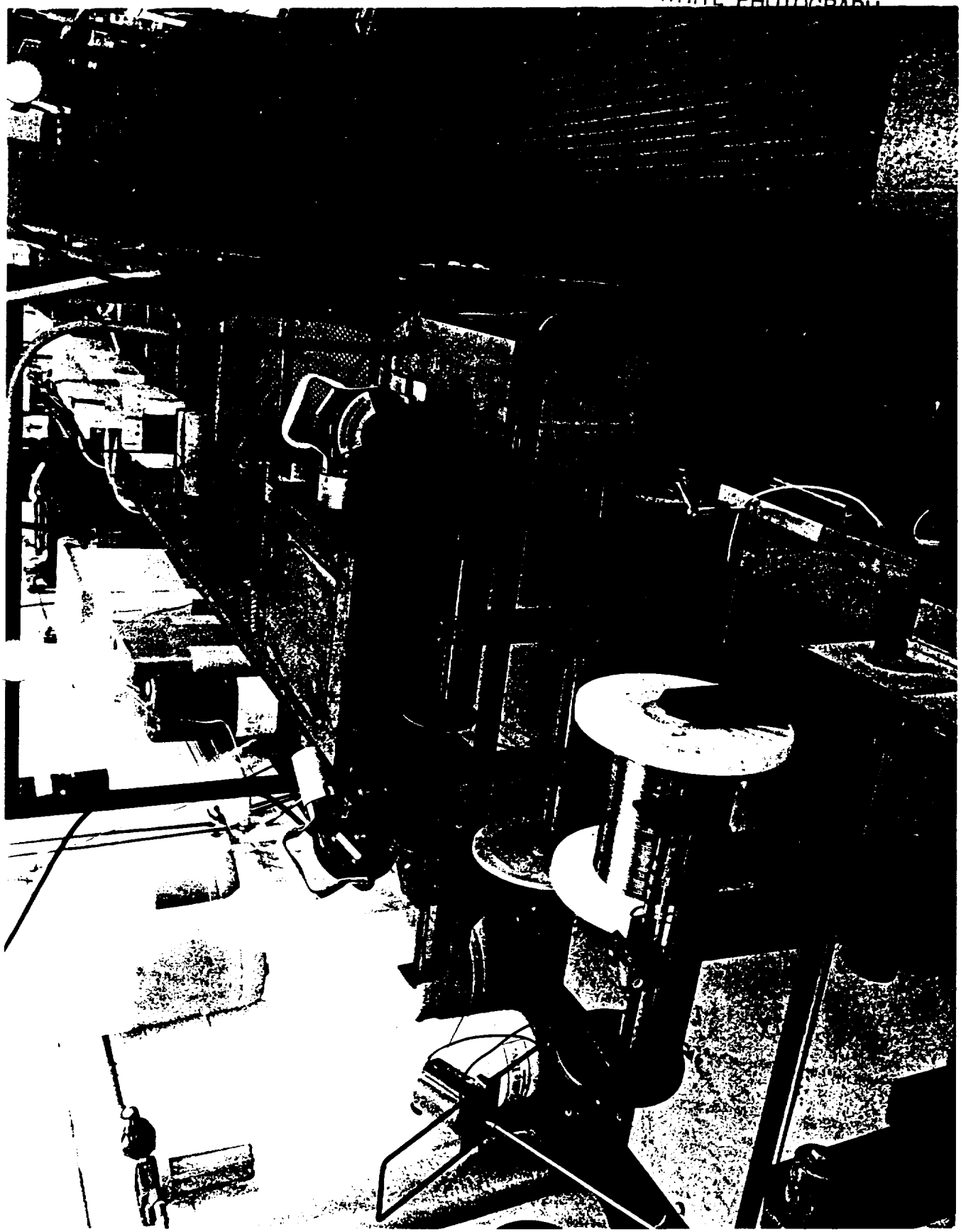


FIGURE 3. METAL-COATED KEVLAR REEL AT END OF PLATING LINE

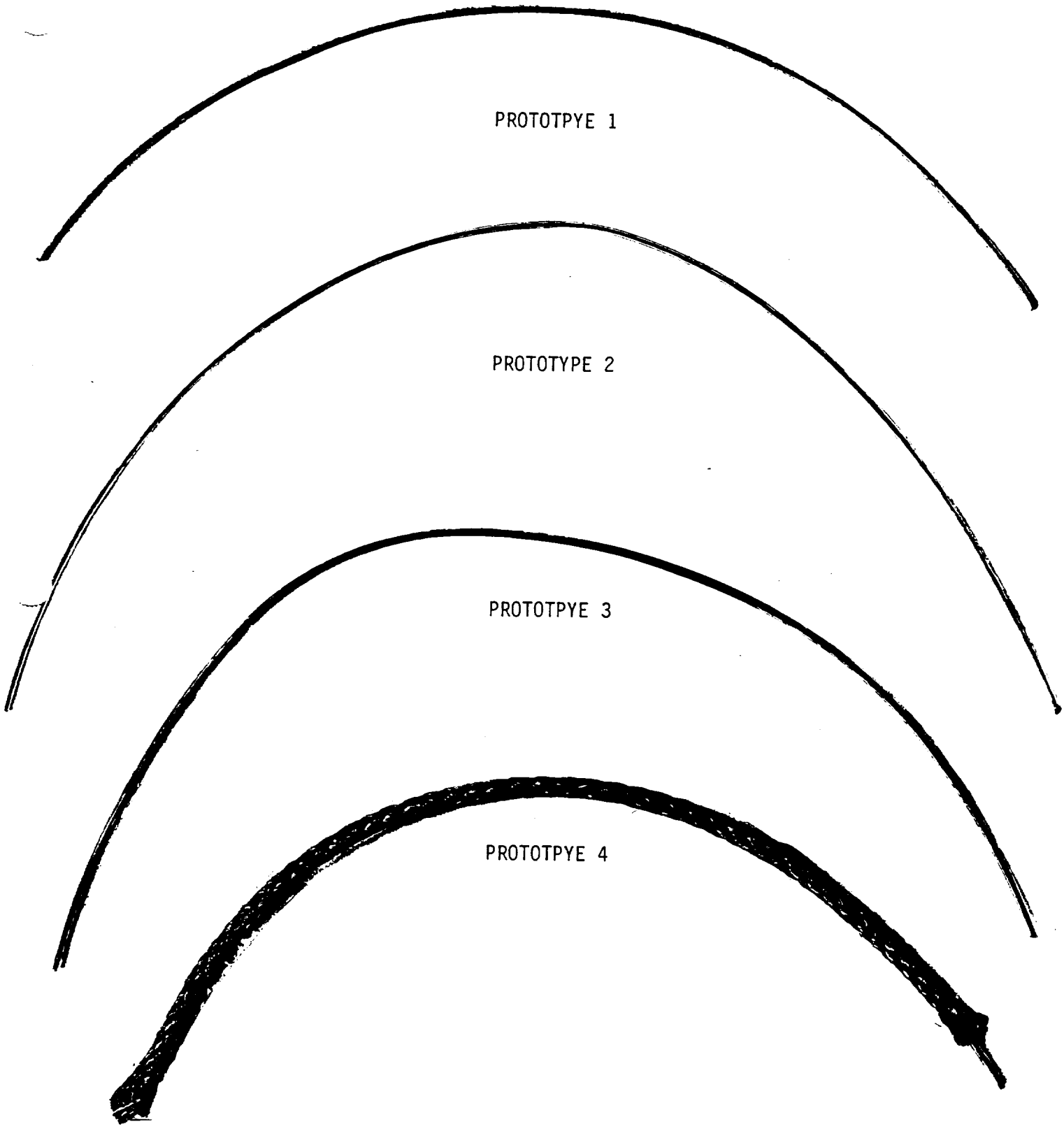


FIGURE 4. FOUR PRELIMINARY PROTOTYPE TETHER CONSTRUCTIONS

Prototype 2: 1 tow of copper-coated Kevlar 49--tubing extruded with a 11 mil wall thickness of Teflon FEP

Prototype 3: 1 tow of copper-coated Kevlar 49--tubing extruded with a 11 mil wall thickness of Teflon PFA

Prototype 4: 3 tows of copper-coated Kevlar 49 in a parallel lay configuration--tubing extruded with a 11 mil wall thickness of Teflon PFA

The Teflon (FEP and PFA) and Tefzel are DuPont registered fluoropolymers.

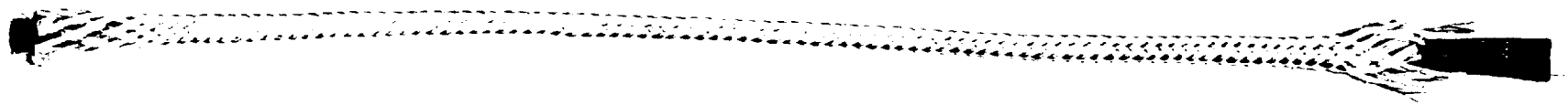
All of the above samples were then tested; this included exposure in the Plasmoid unit at Marshall Space Flight Center which will be discussed later.

To determine whether metal-coated Kevlar would present any problems when woven or braided, 4000 feet of Kevlar 49 was coated with 0.95 micron of copper and 0.05 micron of nickel and sent to Fiber Materials, Inc. (FMI), Biddeford, Maine, along with Prototype 4 above. The object was to braid the copper/nickel-coated Kevlar over the core (Prototype 4), which was three tows of copper-coated Kevlar with the extruded Teflon PFA insulation.

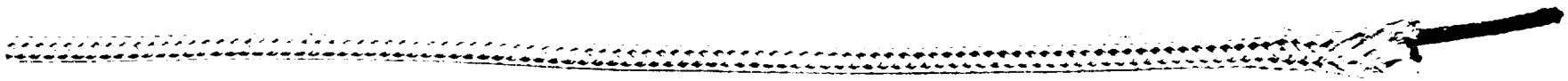
FMI placed a 26 carrier braid of the copper/nickel-coated Kevlar over the Prototype 4 core and reported that no problems were encountered. The resultant product was a totally synthetic coaxial cable.

Final Tether Configurations

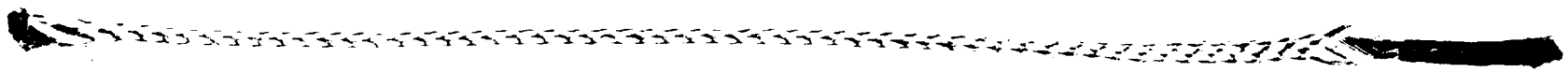
For the final space tether prototype configurations, three designs were selected (Figure 5):



8 TOW, NOMEX JACKET



8 TOW, TEFLON COATING, NOMEX JACKET



3 TOW, NOMEX JACKET

FIGURE 5. FINAL PROTOTYPE TETHER CONSTRUCTIONS

- 1000 feet of metal-coated Kevlar, 8 tows in a parallel lay, overbraided with a tight Nomex jacket

- 1000 feet of metal-coated Kevlar, 8 tows in a parallel lay, extruded with Teflon and overbraided with a tight Nomex jacket

- 1000 feet of metal-coated Kevlar, 3 tows in a parallel lay, overbraided with a tight Nomex jacket

The first configuration (i.e., the eight tow, parallel lay construction) was designed to duplicate the physical load capability of the Martin-Marietta/Cortland Cable Co. tether prepared under an earlier program.* The addition of the Teflon coating to the second design would indicate whether this additional insulation is necessary for protection against atomic oxygen. The third, lighter tether design (i.e., the three tows of 1000 filaments each in a parallel lay) would have potential use in the Get Away Special/Free Flier-type of experiment.

Nineteen thousand feet of Kevlar 49 (1420 denier, 1000 filaments per tow) were coated with 0.95 micron copper and 0.05 micron nickel. As was previously mentioned, the nickel overcoat is added to keep the copper from oxidizing. Eight thousand feet of product was shipped to DuPont, which extruded a 1000-foot section (eight tows in a parallel lay configuration) with Teflon. DuPont reported that they experienced no major problems in handling and preparing the material, and returned the finished 1000 feet to MCI. MCI then sent it along with the remaining

*Design and Fabrication of the 20Km/10Kv Electromechanical Tether for TSS-1 Using High Impact Conductor (HIWIRE), E. Scala, L.S. Marshall, and D.P. Bentley, Tethers in Space, Advances in the Astronautical Sciences, Vol. 62, American Astronautical Society, 1987.

11,000' of Cu/Ni-coated Kevlar to FMI for final construction. FMI braided 1200 denier Nomex over each of the three constructions at a 45 degree angle to achieve a tight braid that would hold the parallel lays of metal-coated Kevlar together.

When the three finished prototype constructions were returned to MCI, they were inspected and tested. Samples of each were also sent to NASA-Marshall for simulated atomic oxygen exposure.

TESTING AND RESULTS

A variety of tests were performed on samples, which included determination of break-load strength and electrical resistivity and visual examination both before and after simulated atomic oxygen exposure in the NASA-Marshall Plasmoid unit.

Verification of Phase I Work

During the Phase I program, MCI found 8 to 12 percent reductions in break-load strength for Kevlar 49 metal coated to a 1 micron level. Testing followed the MCI QCP-2 Yarn Test Procedure (Appendix A) which is used at MCI to test graphite fiber. In talking with a representative at DuPont, doubt was expressed that metal coating should produce such a reduction. Another question which plagued the Principal Investigator involved quality of metal coating. Kevlar inherently contains low percent water. Further, the MCI metal-coating process is done entirely in aqueous solutions. Although a drying step is used at the end of the process, it seems entirely possible that the coated Kevlar still contains some moisture. In addition, although the integrity of the coating seemed to be entirely satisfactory on Earth, the question arose of what would happen when the material was placed in a space environment--a vacuum. Would any residual moisture escape from the Kevlar and destroy or disrupt the metal coating?

Sample quantities of Kevlar 49 coated with 1 micron of copper were sent to DuPont for testing. DuPont tested break strengths of plain, uncoated (Greige) Kevlar and copper-coated material before and after seventy-three (73) hours in vacuum. Results are shown in Table 1. Further, DuPont stated that the copper-coated samples were as strong as the Greige ones and had slightly higher elongation to break (1.92% vs. 1.82%). The elongation differences could be attributed to clamping effects, since DuPont determined elongation based on clamp separation distance rather than with an extensometer. They also looked, with the aid of an optical microscope, at the samples of control and vacuum exposed yarn, and could see no disruption of the copper coating. "Scotch tape testing" of the samples showed no substantial difference in adhesion. (Note: The tape test is a standard test to determine adhesion of plating; a piece of Scotch tape is placed on the plated or metal-coated surface and pulled off to determine adhesion of the coating.)

DuPont was also interested in the abrasion resistance of metal-coated Kevlar; Kevlar filaments within a bundle (or tow) will abrade against one another. Four samples of Kevlar were metal coated and sent to DuPont:

(1) Kevlar 49 coated with 1 micron of copper
(2) Kevlar 49 coated with 0.15 micron of copper
(3) Kevlar 49 coated with 0.25 micron of phosphorus nickel
(4) Kevlar 49 coated with 0.25 micron of boron nickel

The three different metal coatings were selected to determine if metal type had any effect, while two coating levels for copper were selected to see if "more is better".

DuPont's tests showed that Items 1,2, and 3 above out-performed the Kevlar 49 (uncoated) control by a factor of twenty-five. Item 4 gave mixed results: from no improvement for some

TABLE 1. BREAK STRENGTHS OF SINGLE TOWS OF KEVLAR 49

Sample	Kevlar 49 Break Strength*, lb	
	Control	After Exposure**
Greige (Plain, Uncoated)	54.1 (3.4)	52.2 (1.9)
Copper Coated	55.4 (2.7)	55.0 (1.8)

Notes:

* Value in () is standard deviation based on five replicas.
** 73 Hours in vacuum.

samples to that of the other three items. It was later determined that coating consistency of Item 4 was below standard and thus accounted for the varied results.

Preliminary Single-Tow Prototypes

The first three preliminary prototypes tested were the single tow samples of copper-coated Kevlar 49 which had been extruded with Teflon and Tefzel by DuPont; the fourth prototype comprised the three tows of copper-coated Kevlar and was extruded with Teflon; it was to be used in a coax configuration. Visual examination showed that all extruded coatings were of good quality and were uniform over the entire length of each sample. The copper coating was not affected by the extrusion process for the single end (one tow) samples, but the one sample consisting of three ends (i.e., three 1,000-filament tows) of copper coated Kevlar showed dark areas indicating oxidation of the copper. Electrical resistance measurements of the three-end sample were higher than one would expect; this would also indicate some oxidation of the copper coating. A nickel overcoat would be used in an actual tether construction to prevent this problem.

Samples of the first three single tow constructions were then sent to NASA-Marshall where they were exposed in one of their Plasmoid plasma etching chambers (i.e., Asher). Conditions for short-term exposure were an oxygen pressure of 2 psi at 50 watts for a period of 5 minutes. A total of eight 6-inch pieces were weighed, loaded, exposed, and reweighed at one time for each type of polymer. Electrical resistance and breakload measurements were made, and data are shown in Table 2 while mass loss data is shown in Table 3. For the electrical resistance measurements, about 3/4-inch of the extruded polymer was removed from each sample. The tubing-extruded polymers (i.e., the Teflons) were very easy to remove with a standard electrical wire stripper which did not damage the metal-coated Kevlar fiber within.

TABLE 2. COMPARISON OF UNEXPOSED AND EXPOSED (SHORT-TERM) SAMPLES OF POLYMER-EXTRUDED COPPER-COATED KEVLAR(*)

Sample	Electrical Resistance Ohms		Breakload, pounds	
	Unexposed	Exposed	Unexposed	Exposed
Teflon FEP-1	0.31	0.52	42.0	33.5
Teflon FEP-2	0.17	0.30	27.0	15.0**
Teflon FEP-3	0.27	0.37	46.5	31.0
Teflon FEP-4	0.49	0.51	23.0	38.0
Teflon FEP-5	0.27	0.47	37.0	30.0
	(AVG.0.302)	(AVG.0.434)	(AVG.35.1)	(AVG.33.1)
Teflon PFA-1	0.10	0.09	23.0	17.5**
Teflon PFA-2	0.15	0.17	31.0	34.0
Teflon PFA-3	0.19	0.13	41.0	35.0
Teflon PFA-4	0.16	0.18	17.5**	9.0**
Teflon PFA-5	0.19	0.11	43.0	48.5
	(AVG.0.158)	(AVG.0.136)	(AVG.34.5)	(AVG.39.2)
Tefzel-1	0.28	0.23	35.0	15.0**
Tefzel-2	0.18	0.34	19.0**	11.0
Tefzel-3	0.31	0.28	19.0**	19.5
Tefzel-4	0.31	0.17	27.0	14.0**
Tefzel-5	0.26	0.22	35.0	20.5
	(AVG.0.268)	(AVG.0.248)	(AVG.32.3)	(AVG.17.0)

*Samples consisted of 6-inch lengths of copper coated Kevlar 49 (1.0 micron coating), 1420 denier, 1 end of 1000 filaments. Each was extruded with a 11 mil wall thickness of the indicated polymer.

**The sample broke in stages which indicates that it was not properly mounted in the grips. Therefore, this data was discounted and not included in calculating the average value below.

TABLE 3. SHORT-TERM MASS LOSS DATA FOR POLYMER-COATED KEVLAR TETHER PROTOTYPES*

Sample	Initial Wt., g**	Final Wt., g**	Difference, g**	% Wt. Loss
Single tow of Cu-coated Kevlar 49 w/Teflon FEP	3.19066	3.18639	0.00427	0.13
Single tow of Cu-coated Kevlar 49 w/Teflon PFA	3.45667	3.45284	0.00383	0.11
Single tow of Cu-coated Kevlar 49 1/Tefzel	2.69603	2.69316	0.00287	0.11

* Exposure conditions: 2 psi O_2, 50 watts, 5 minutes.
** Weights are for 6-8 inch lengths.

However, the pressure-extruded Tefzel was very difficult to remove without damaging several of the metal-coated Kevlar fibers.

A standard multimeter was then used to measure the electrical resistance of each 6-inch piece of material. (Note, the internal resistance of the meter and test leads were subtracted from the measured values to determine the actual values.)

The same samples were then tested with an Instron TMS 1102 tensile tester. Prior to testing, the bare ends of each sample were coated with epoxy and allowed to dry. Sandpaper was placed in the grips to keep the sample from slipping out of the grips. It is important to note that MCI's test procedure for determining breakload differs from the one used by DuPont. Consequently, it was expected that MCI's values for even the unexposed samples would be somewhat lower than those obtained by DuPont. Since the test procedure for unexposed versus exposed samples would be the same, then the data collected would be valid for comparison purposes even though the actual values would not.

Trends gained from the above two tests indicated that the electrical resistances for the Tefzel and Teflon PFA extruded materials were not affected by exposure, but the Teflon FEP was raised (i.e., there was a loss in conductivity). For breakload strengths, Teflon PFA did not lose any strength, while Teflon FEP experienced a modest loss. Tefzel experienced the greatest loss, but it should again be mentioned that in stripping the Tefzel from the Kevlar, Kevlar fibers were damaged, so actual values may not have been as severe as shown in the table. Also, all breaks occurred in the grip; no breaks occurred in the gage length.

Only one piece of each type of extruded polymer shown in Tables 2 and 3 was exposed for a long term. Conditions were the same as for the short-term exposures except that each sample was exposed for 15 minute intervals up to a total exposure of 1 hour.

Because only one sample of each was exposed long term, only mass loss data was obtained (Table 4).

Preliminary Coax Prototype

The fourth prototype material was the coax configuration: a core made of 3 tows (1000 filaments each) of copper-coated Kevlar 49 which was extruded with Teflon PFA; overbraid consisted of a 26 carrier braid of Kevlar containing 0.90 micron copper and 0.10 micron nickel (Figure 6). Short- and long-term exposures were performed at NASA-Marshall in the Plasmoid, and mass loss data are given in Table 5 and 6.

Microscopic examination of short- and long-term exposure samples did not reveal any extensive damage when compared to unexposed samples. A few fibers on the outside jacketing were found to be broken on samples exposed for the short term, while slightly more damage was found on the sample exposed for the long term. No degradation was found with the Teflon coating or core material for either sample.

Because microscopic examination is rather subjective and not entirely conclusive, samples were additionally examined to determine if electrical resistance had been affected by exposure in the Plasmoid chamber. The inner core (Teflon and copper-coated Kevlar) was removed from the outer jacketing for an unexposed sample, a short-term exposed sample, and the long-term sample. For the core material, the Teflon insulation was stripped from each end, and the sample was connected to a variable voltage/variable current d.c. power supply. As shown in Table 7, 0.2, 0.3, and 0.4 voltages were applied to the sample and the corresponding current recorded. (Because metal-coated fibers and fabrics behave as resistive heaters when subjected to an electric current, samples heated up during these tests.) The same test was performed on the outer jacketing material for each sample.

TABLE 4. LONG-TERM MASS LOSS DATA FOR POLYMER-COATED KEVLAR TETHER PROTOTYPES*

Exposure Time, min.	Weight, g	% Wt. Loss
	Copper-Kevlar With Teflon FEP	
0(initial)	0.42707	----
15	0.42561	0.34
30**	0.42455	0.59
45	0.42338	0.86
60	0.42236	1.10
	Copper-Kevlar With Teflon PFA	
0(initial)	0.36935	----
15	0.36791	0.39
30	0.36659	0.75
45	0.36497	1.20
60	0.36376	1.50
	Copper-Kevlar With Tefzel	
0(initial)	0.34261	----
15	0.34166	0.28
30	0.34106	0.45
45	0.34051	0.61
60	0.33981	0.82

* Exposure conditions: 2 psi O_2, 50 watts.

** After 30 minutes, Teflon appeared cloudy; exposed copper darkening.

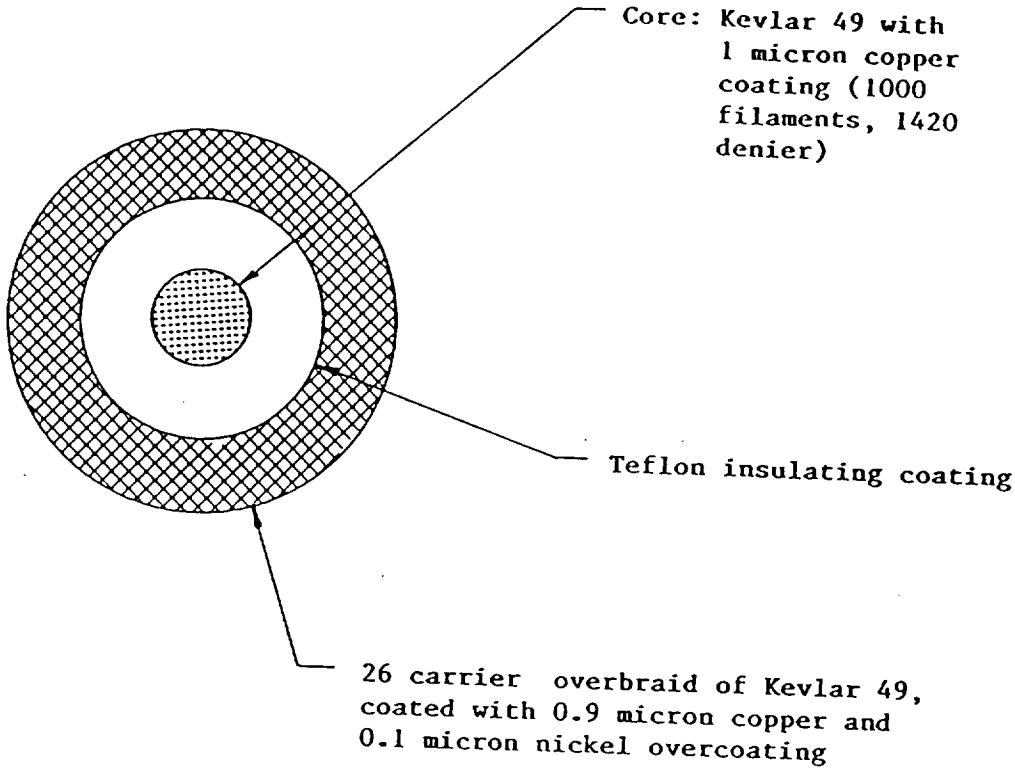


FIGURE 6. OVERBRAIDED TETHER SAMPLE

TABLE 5: SHORT-TERM MASS LOSS DATA FOR COAX PROTOTYPE*

Sample**	Initial Weight,g	Final Weight,g	Weight Loss,g	%wt.loss
1	1.75390	1.74046	0.01344	0.77
2	1.73947	1.72525	0.01422	0.82
3	1.69552	1.68122	0.01430	0.84
4	1.63708	1.62327	0.01381	0.84
5	1.74000	1.72512	0.01488	0.86
			Average	0.83

* Exposure conditions: 2 psi O_2, 50 watts, 5 minutes.

** Each sample of material individually exposed.

TABLE 6: LONG-TERM MASS LOSS DATA FOR COAX PROTOTYPE*

Exposure Time, min.	Weight, g	% wt. loss
0 (initial)	1.72475	----
15	1.70241	1.30
30	1.69306	1.84
45	1.68385	2.37
60	1.67556	2.85

* Exposure conditions: 2 psi O_2, 50 watts.

TABLE 7. ELECTRICAL CHARACTERIZATION OF TETHER SAMPLES

Sample (Length, in.)	Resistance Meas,ohms*	D.C. Input Power, volts/amps (watts)	Temperature Increase, °C	Resistance Calc., ohms**	Resistance/In., ohms	Avg. Resistance/ Foot, ohms
Core, unexposed (11)	0.5	.20/.45 (.09)	0	.4444	.0404	
		.30/.69(.207)	1	.4348	.0395	.4776
		.40/.92(.368)	2	.4348	.0395	
				(Avg. .4380)	(Avg. .0398)	
Core, short-term exposure (7-3/4)	0.3	.20/.82(.164)	1	.2439	.0325	
		.30/1.23(.369)	3	.2440	.0315	.3840
		.40/1.62(.648)	7	.2469	.0319	
				(Avg. .2449)	(Avg. .0320)	
Core, long-term exposure(7-11/16)	0.3	.20/.72(.144)	1	.2778	.0361	
		.30/1.12(.336)	3	.2679	.0348	.4248
		.40/1.48(.592)	6	.2703	.0352	
				(Avg. .2720)	(Avg. .0354)	
Outer Jacket, unexposed (11)	0.3	.20/.52(.104)	1	.3846	.0350	
		.30/.81(.243)	2	.3704	.0337	.4080
		.40/1.09(.436)	6	.3670	.0334	
				(Avg. .3740)	(Avg .0340)	
Outer Jacket, short-term exposure (7-3/4)	0.4	.20/.64(.128)	1	.3125	.0403	
		.30/.99(.297)	7	.3030	.0391	.4752
		.40/1.31(.524)	13	.3056	.0394	
				(Avg .3069)	(Avg .0396)	
Outer Jacket, long-term exposure (7-11/16)	0.9	.20/.23(.046)	1	.8696	.1131	
		.30/.38(.114)	3	.7895	.1027	1.2792
		.40/.50(.200)	5	.8000	.1041	
				(Avg .8197)	(Avg .1066)	

*-Measured with a multimeter.
**-Calculated from power(watts)=volts x amps, and power(watts)=V^2/R.

From the formula volts (V) x amps (A) = power (watts) and power (watts) = V^2/R, the actual resistance (R) of each sample was calculated and compared to that measured with a multimeter. Because sample lengths varied, the resistance per inch was calculated, and then the average resistance per foot of material was determined.

From the table, it is apparent that neither the short-term nor the long-term exposure affected the inner core portion of the tether. Although the outer jacketing experienced a modest gain in resistance for the short-term exposure samples, resistance was found to be about three times greater for the long-term exposure sample than for the unexposed material.

Apparently, the long-term exposure did affect the outer jacketing material, but the inner core was protected by the outer jacketing.

Final Tether Configurations

The final three tether configurations were the two eight-tow constructions and the one three-tow construction. To determine the electrical resistances of the samples, 5 foot samples of each were connected to a d.c. power supply. Known voltages and amperages were passed through the samples. Again, from the formula volts x amps = power (watts), the power was calculated and from the formula $volts^2/R(ohms)$ = watts the resistances were calculated (Table 8).

Sample 1 was the 8 tows of Kevlar 49 which were coated with 0.9-0.95 micron of copper plus a 0.05-0.01 micron nickel overcoat; this material was then overcoated with Teflon FEP (by DuPont) and the entire construction was overbraided with a Nomex jacket. The average resistance per foot of tether was 0.07 ohm.

TABLE 8. RESISTANCES OF TETHER PROTOTYPES

Material	Power (5 ft. Sample) Volts/Amps (Watts)	Resistance (5 ft. Sample), ohms		Resistance for 1 foot, ohms
Sample 1:				
8 tows Cu/Ni	0.50/1.42 (0.71)	0.35		0.07
Kevlar with	0.75/2.15 (1.613)	0.348		0.07
Teflon jacket				
and Nomex overbraid	1.00/2.88 (2.88)	0.347		0.07
			Avg.	0.07
Sample 2:				
8 tows Cu/Ni	0.50/1.70 (0.85)	0.294		0.059
Kevlar with Nomex	0.75/2.57 (1.928)	0.292		0.058
overbraid	1.00/3.44 (3.44)	0.291		0.058
			Avg.	0.058
Sample 3:				
3 tows Cu/Ni	0.50/0.48 (0.24)	1.04		0.208
Kevlar with Nomex	0.75/0.72 (0.54)	1.04		0.208
overbraid	1.00/0.96 (0.96)	1.04		0.208
			Avg.	0.208

Sample 2 was identical to Sample 1, except that there was no Teflon FEP extruded over the metal-coated Kevlar. Average resistance for this material was 0.058 ohm per foot.

The third sample (Sample 3) was identical to the second sample except that only three tows of metal-coated Kevlar were used instead of eight. Here, the average resistance was 0.208 ohm per foot.

Results of measurements made on all three prototype constructions were very consistent. In addition, it should be remembered that each 1000-filament tow used in these constructions had an average resistance of 0.7 ohm per foot.

Following the above work, tensile testing was performed on the three samples (Table 9). In testing the tether material, ASTM D2256-80, "Breaking Load and Elongation of Yarn by the Single-Strand Method", was followed as closely as possible.* The grips that were used were the Instron cord capstan grips, and the gage length was 10 inches. The strain rate was approximately 0.20 in./sec., while the approximate time for a sample was between 12 and 20 seconds. The recommended time per sample is 20 seconds.

The percent elongation results cannot be taken as a true average value because not nearly enough samples were taken. The recommended number of samples from the ASTM procedure is 60.

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*The ASTM method and description of special Instron grips are presented in Appendix B.

TABLE 9. BREAK-LOAD VALUES FOR TETHER PROTOTYPES

Material: Sample 1 - 8 tows with Teflon plus Nomex			
Number of samples:	5		
Average break-load:	333.0 pounds	Std deviation:	3.1%
Percent elongation:	34.5	Std deviation:	17.1%
Material: Sample 2 - 8 tows with Nomex			
Number of samples:	15		
Average break-load:	368.3 pounds	Std deviation:	7.3%
Percent elongation:	24.7	Std deviation:	5.3%
Material: Sample 3 - 3 tows with Nomex			
Number of samples:	5		
Average break-load:	175.6 pounds	Std deviation:	2.7%
Percent elongation:	16.2	Std deviation:	6.8%

Note that during the testing of the one 8 tow material, the outer sheath failed at a greater elongation but lower load after the initial failure of the core material. During the 8-tow-with-Teflon test, the Teflon did not fail. The failure mode consisted of the initial break, after which the material would sustain a reduced load. This was followed by several more failures before the ultimate failure of the material.

The average break-load for uncoated Kevlar 49 (1000 filament, 1420 denier) is 54 pounds. Therefore, for eight tows of material, a projected break-load would be 432 pounds. Testing showed values of 333 pounds for Sample 1 and 368.3 pounds for Sample 2. For the three tow construction (Sample 3), one would expect a break-load of 162 pounds, but it was somewhat higher than predicted (175.6 pounds).

The final tether configurations exposed in the Plasmoid plasma chamber at the Marshall Space Flight Center were then examined. Exposure conditions were as follows: oxygen pressure was 2 psi; power was 50 watts; short-term exposure was for 5 minutes and long-term exposure was for 1 hour. For the long-term exposure, samples were removed and weighed at 15 minute intervals. Five samples of each construction were exposed for the short-term tests, while one sample of each construction was exposed for the long-term test.

Table 10 presents data for the short-term exposure for Sample 1, which was eight tows (1000 filaments per tow) of Kevlar 49 coated with 0.90-0.95 micron of copper plus a 0.05-0.10 micron nickel overcoat. The metal-coated Kevlar was overbraided with a Nomex jacket. Table 11 presents the long-term exposure data for the same material. Tables 12 and 13 present the short- and long-term exposure data for Sample 2, which was the same construction

TABLE 10. SAMPLE 1 — SHORT-TERM EXPOSURE*

Sample:	1A	1B	1C	1D	1E
Initial Weight, g:	1.22764	1.24505	1.17480	1.18933	1.14834
Final Weight, g:	1.21245	1.22238	1.15340	1.16925	1.12816
Weight Loss, g:	0.01519	0.02267	0.02140	0.02008	0.02018
Weight Loss, %:	1.24	1.82	1.82	1.69	1.76
		(Avg. 1.67%)			

* Eight tows of Kevlar 49 (1000 filaments per tow) were coated with 0.90-.95 microns of copper and 0.05-.10 microns of nickel; Nomex overbraid. (2 PSI oxygen, 50 watts power, 5 min. exposure)

TABLE 11. SAMPLE 1 — LONG-TERM EXPOSURE*

Exposure Time, min.	Weight, g	Weight Loss, g	Weight Loss, %
0	1.15752	0	---
15	1.10847	0.04905	4.2
30	1.06787	0.08965	7.7
45	1.02736	0.13016	11.2
60	0.98841	0.16911	14.6

* Eight tows of Kevlar 49 (1000 filaments per tow) were coated with 0.90-0.95 micron of copper and 0.05-0.10 micron of nickel; Nomex overbraid.
(2 PSI oxygen, 50 watts power, 60 min. exposure)

Table 12. SAMPLE 2 — SHORT-TERM EXPOSURE*

Sample:	2A	2B	2C	2D	2E
Initial Weight, g:	0.44837	0.44948	0.45396	0.43765	0.45506
Final Weight, g:	0.43516	0.43585	0.44011	0.42318	0.44088
Weight Loss, g:	0.01321	0.01363	0.01385	0.01447	0.01418
Weight Loss, %:	2.95	3.03	3.05	3.31	3.12
		(Avg. 3.09%)			

* Three tows of Kevlar 49 (1000 filaments per tow) were coated with 0.90-0.95 micron of copper and 0.05-0.10 micron of nickel; Nomex overbraid. (2 PSI oxygen, 50 watts power, 5 min. of exposure)

TABLE 13. SAMPLE 3 — LONG-TERM EXPOSURE*

Exposure Time, min.	Weight, g	Weight Loss, g	Weight Loss,%
0	0.43897	0	----
15	0.39822	0.04075	9.3
30	0.36832	0.07065	16.1
45	0.33340	0.10557	24.0
60	0.30625	0.13272	30.2

* Three tows of Kevlar 49 (1000 filaments per tow) were coated with 0.90-0.95 micron of copper and 0.05-0.10 micron of nickel; Nomex overbraid. (2 PSI oxygen, 50 watts power, 60 min. exposure)

as Sample 1 except that it contained only three tows of metal-coated Kevlar. Tables 14 and 15 present the short- and long-term exposure data for Sample 3, which was the same construction as Sample 1 except that a Teflon coating was extruded over the metal-coated Kevlar prior to overbraiding with Nomex.

Microscopic inspection of the samples was conducted with the following observations. For Sample 1, the short-term exposure showed no damage to either the Nomex outer jacket or the inner metal-coated Kevlar core. The piece exposed for a long term, however, showed considerable damage to the Nomex jacket (Figure 7). A small amount of damage to the inner core was also detected. The same conditions were noted for Sample 2: no damage for the short-term exposures, but considerable damage to the Nomex for the long-term exposure. In addition, for the long-term exposed piece some of the outer filaments of metal-coated Kevlar in the core were damaged and broken. For Sample 3, which had the Teflon extruded over the core material, the short-term pieces showed no damage. The piece exposed for the long term showed some damage to the Nomex, but it was not as severe as that which was noted on the previous samples. Further, the Teflon and metal-coated Kevlar core also showed no damage under long-term exposure.

As shown in the accompanying tables, average weight loss for short-term exposed samples was the least for the eight tow material which had the Teflon overcoat and the greatest for the three-tow material. This trend was also true for material exposed for the long term. Apparently, the Teflon protects the inner core material, and even a larger volume of metal-coated Kevlar protects the inner Kevlar (i.e., 8 vs. 3 tows). Outer Nomex jacket damage was about the same for both the eight tow and three tow samples, but was somewhat less for the material which had the Teflon.

FIGURE 7. SAMPLE 1 — LONG-TERM DAMAGE

TABLE 14. SAMPLE 3 – SHORT-TERM EXPOSURE*

Sample:	3A	3B	3C	3D	3E
Initial Weight, g:	1.97071	1.89895	1.86997	1.91149	1.96790
Final Weight, g:	1.94980	1.87775	1.84877	1.88890	1.94569
Weight Loss, g:	0.02091	0.02120	0.02120	0.02259	0.02221
Weight Loss, %:	1.06	1.12	1.13	1.18	1.13
		(Avg. 1.12%)			

* Eight tows of Kevlar 49 (1000 filaments per tow) were coated with 0.90-.95 micron of copper and 0.05-0.10 micron of nickel; Teflon extruded overcoat plus Nomex overbraid.
(2 PSI oxygen, 50 watts power, 5 min. exposure)

TABLE 15. SAMPLE 3 – LONG-TERM EXPOSURE*

Exposure Time, min.	Weight, g	Weight Loss, g	Weight Loss, %
0	1.93197	0	----
15	1.87822	0.05375	2.8
30	1.83410	0.09787	5.1
45	1.79046	0.14151	7.3
60	1.74799	1.83980	9.5

* Eight tows of Kevlar 49 (1000 filaments per tow) were coated with 0.90-0.95 micron of copper and 0.05-0.10 micron of nickel; Teflon extruded overcoat plus Nomex overbraid.
(2 PSI oxygen, 50 watts power, 60 min. exposure)

Tether Damping Study

During August 1987, the Principal Investigator attended the NASA Tether Applications in Space Summer Review in McLean, Virginia, and presented a short review of this program to attendees. During the course of this meeting, the problems associated with damping characteristics of tethers was discussed and the question arose as to whether the damping characteristics of Kevlar are changed by metal coating. To answer the question, samples of metal-coated and uncoated Kevlar 49 were sent for testing to Anco Engineers, Inc. of Culver City, California.

Testing consisted of a series of excitations on the tethers while under static tensions. Excitation and responses were measured using small accelerometers and recorded as time and frequency domain plots. Based upon this data, an analysis of the transfer function (using the excitation signal as the base) of both types of tethers were determined. Differences between the two were noted, and a determination of differences in damping function (if any) were made.

Specifically, each test tether was suspended vertically. An initial pre-load (approximately equal to 25% of the computed break strength of 90 lbs. or 400 N) was installed to stretch the specimen. For the longitudinal tests, an additional 10% load was installed and then cut away, creating a measurable disturbance. Lateral testing consisted of a lateral impulse ("plucking") on the tether. In both cases, the disturbance and damping characteristics were transduced from a strain-gaged interface between the tether and its upper support element.

For the actual tests, a mass of 25 lb (11.2 kg) giving a vertical load of 25 lb (112 N) was installed to stretch the tether specimen. An additional 6 lb (27 N) load was then tied

onto the end mass. A step disturbance (an amplitude of 6 lb (27 N) was generated when the second mass was cut away. The disturbance and damping characteristics were transduced from a strain-gaged interface between the tether and the upper support point.

Based upon these tests, the following results were generated:

Tether Material	Natural Frequency (Hz)	Stiffness (N/m)	Damping Factor (%)
Kevlar	0.98	431	0.7
Kevlar/Cu-Ni Composite	1.05	485	1.3

Anco's conclusion was that it would appear that the Kevlar/Cu-Ni composite tether has higher damping and is slightly stiffer than the basic Kevlar tether. Note that the damping factors should be used only for the length and end mass used, and would be different if different lengths and masses were involved. However, the relative differences between the two types of tether would not change.

Damping nomographs, damping time histories, and frequency response plots follow Figures 8 through 11.

PRECIOUS METAL COATING

The standard tether configuration for this program was Kevlar 49 with a 1 micron coating of copper for electrical conductivity; a light nickel coating (0.01-0.05 micron) is then deposited over the copper to prevent the copper from oxidizing. The main idea of depositing a precious metal coating over the nickel was to determine if electrical conductivity could be improved upon. The proper method is to deposit the precious metal over nickel,

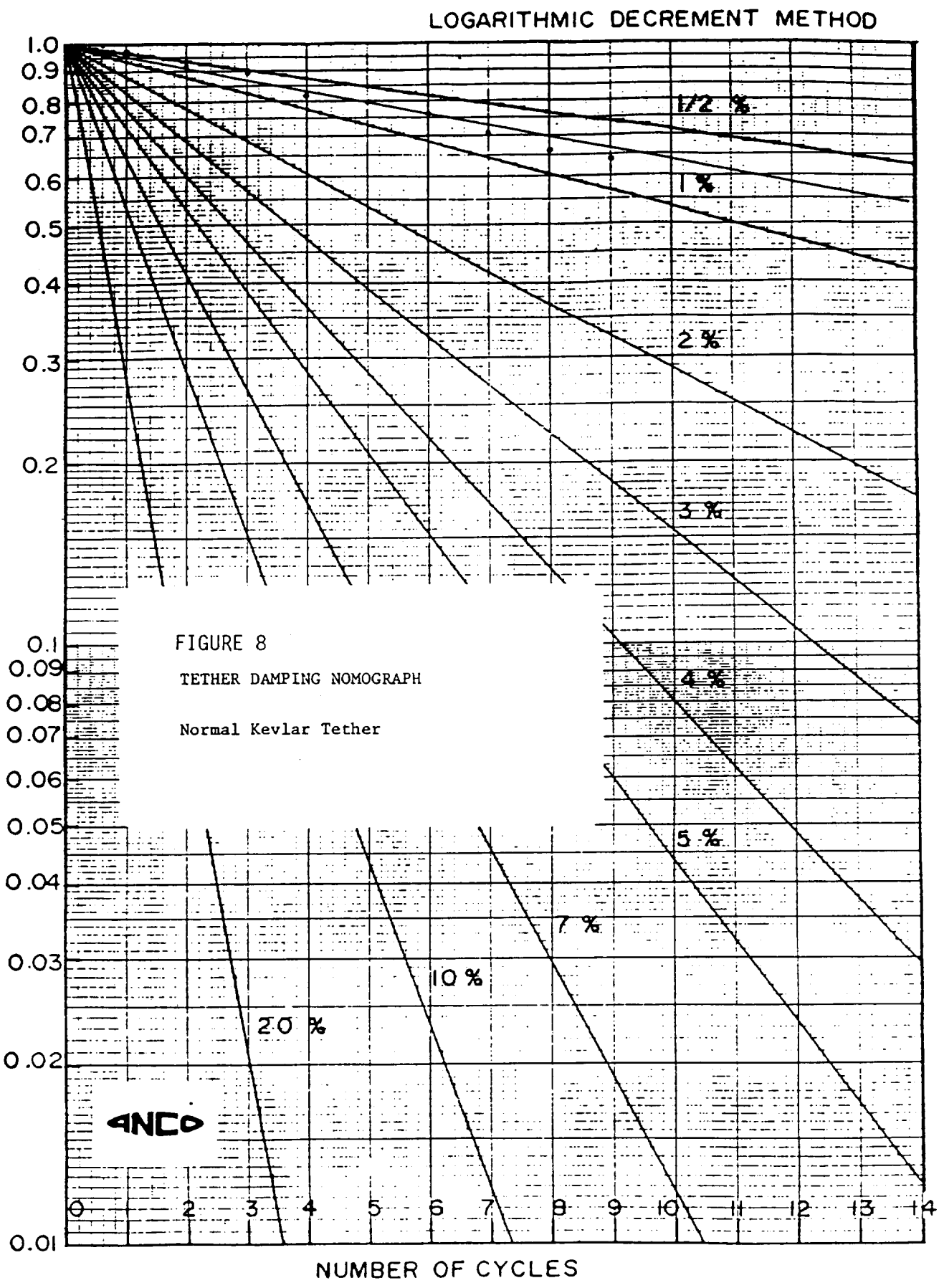


FIGURE 8

TETHER DAMPING NOMOGRAPH

Normal Kevlar Tether

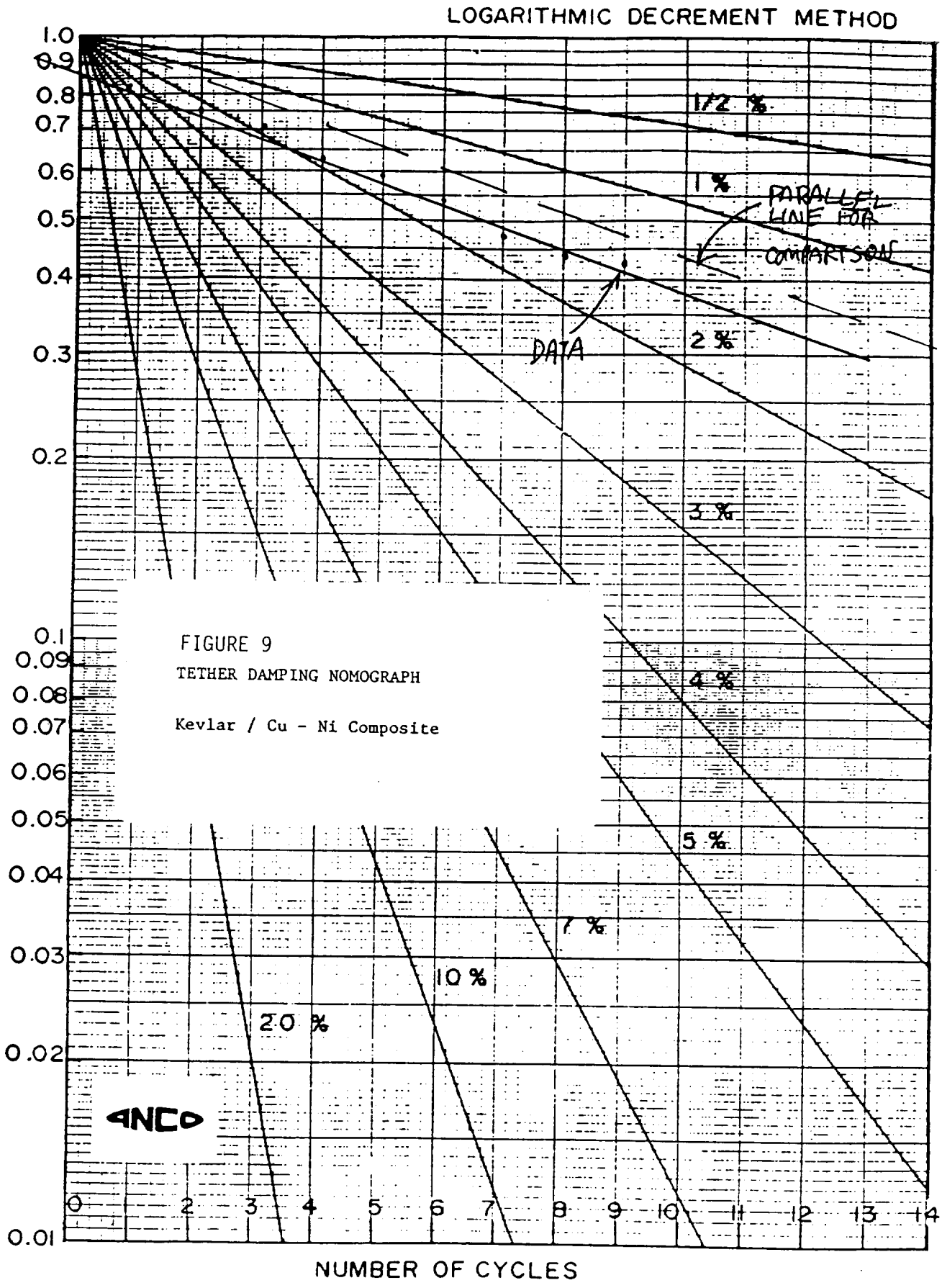
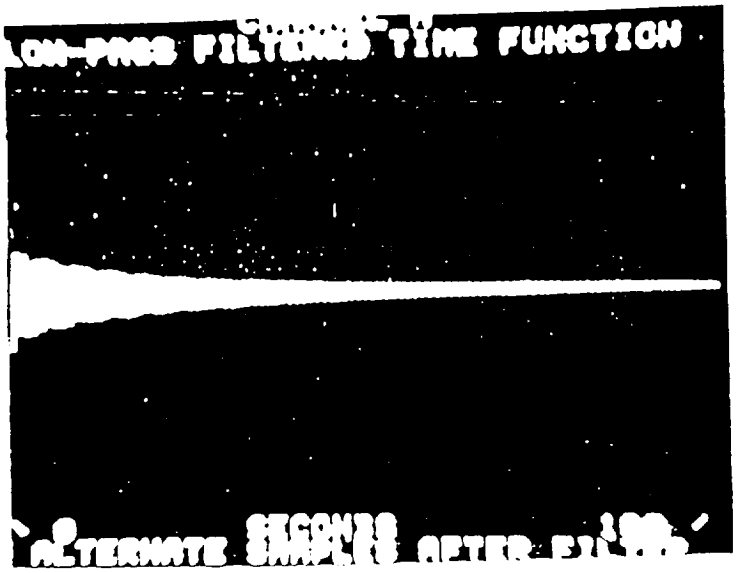


FIGURE 9

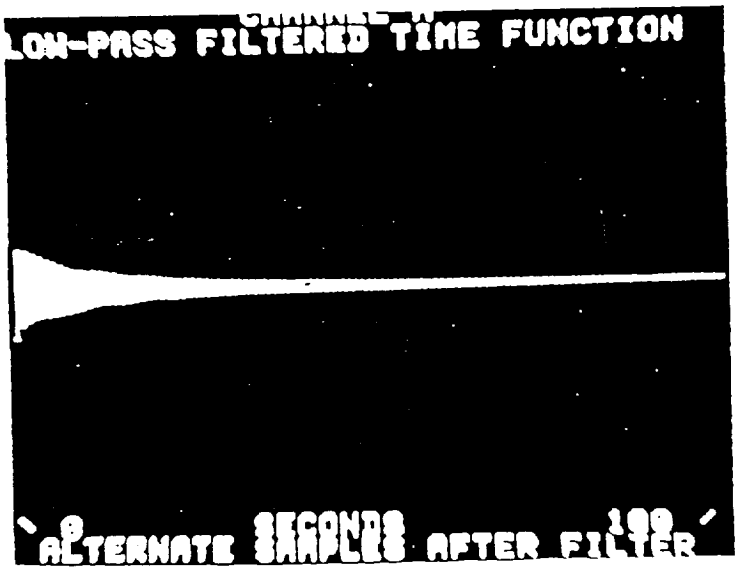
TETHER DAMPING NOMOGRAPH

Kevlar / Cu - Ni Composite



Tether Damping Time History

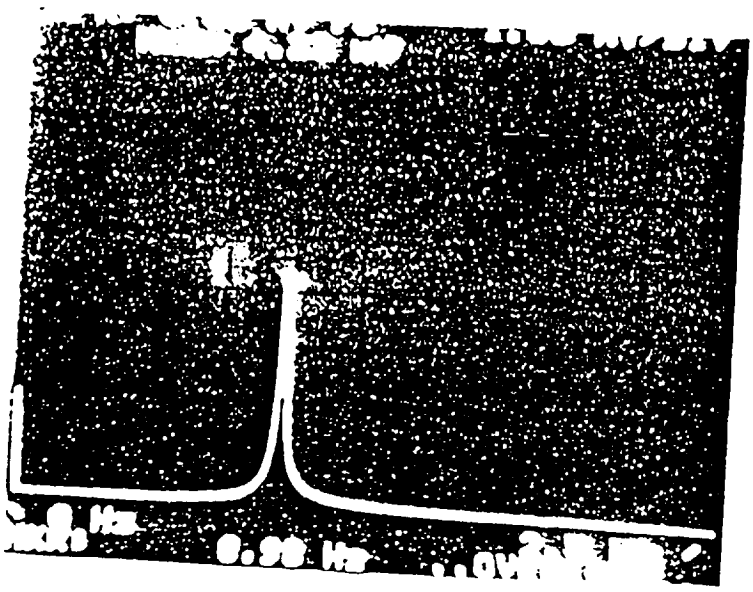
NORMAL KEVLAR TETHER



Tether Damping Time History

KEVLAR / CU - NI COMPOSITE

FIGURE 10



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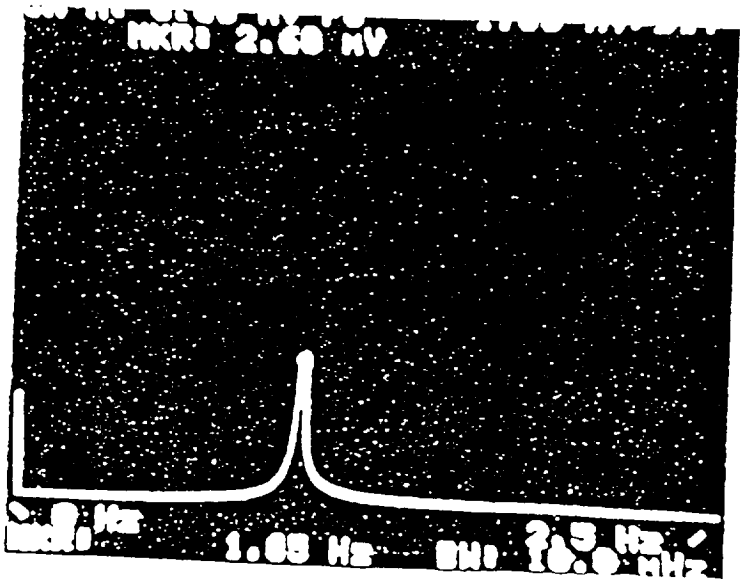
Frequency Response: Normal Kevlar



Frequency Response: Kevlar / Cu - Ni
Composite

FIGURE 11

because if a precious metal is deposited over copper, the copper will eventually migrate into the precious metal and eventually change the characteristics of that layer. During earlier work in the program, a boronated nickel solution was used to deposit nickel because of its superior electrical conductivity. However, the cost of the boronated nickel solutions is fairly high. Therefore, for the precious metal work, a standard Watts electroplated nickel (which is fairly inexpensive) was used.

A special run of Kevlar was prepared with a light gold layer as the final coating. At the time it was being deposited onto the copper-coated Kevlar, it appeared to be fairly comparable to the boronated nickel and gave electrical resistances on the order of 0.5 ohm per foot; however, upon measuring the nickel later during comparison measurements with the gold, it was found to be much higher (i.e., around 3.0 ohms). The addition of gold would lower this to 0.5 ohm per foot, but since the purpose of the experiment was to obtain resistances below 0.5 ohm per foot, this work was discontinued.

COATING OF WIDE FABRIC

Up until midway in the program, all work had been performed with multifilament Kevlar. One concept mentioned at a NASA tether conference was that of a tapered tether system. Here, the tether would be wider at the point of deployment and gradually become narrower towards the payload. In anticipation of this possible need, MCI investigated the metal coating of Kevlar tapes. A sample of a uniform, 1-3/4 inch wide Kevlar tape was procured and successfully coated in MCI's laboratory to prove feasibility. Such a tape can be processed with the existing Pilot Fiber Coating Line at MCI. However, processing of a tapered tether which was over 8 inches in width at any point would necessitate changes to the existing equipment but was considered to be entirely feasible.

To demonstrate this concept, the Pilot Fiber Coating Line was given a quick reconfiguration: some temporary tanks were built and motor drives were re-engineered. Thirty-eight-inch-wide Kevlar fabric was then processed according to the same standard procedure used to metal coat the Kevlar fiber. Because the line was not long enough to coat both the copper and nickel at the same time, it was necessary to coat each metal in a separate pass. As can be seen in Figures 12 through 14, the demonstration was successful.

TERMINATION TECHNIQUES

The electrical connection in a standard tether configuration could be accomplished by several techniques: soldering, crimp-on connectors, splicing, etc. But electrical termination of metal coated Kevlar presents new challenges. Could Kevlar be soldered, especially since it melts at a fairly low temperature when compared to copper wire? Can this material be crimped, and in fact, can the Teflon/Tefzel be stripped from the metal-coated Kevlar?

Some experiments were conducted to determine if soldering was possible. A low-temperature solder was first attempted with a pencil tip soldering gun used to apply the solder. If the tip of the soldering gun was held on the metal-coated Kevlar too long, the Kevlar would indeed melt. However, if heat was applied only long enough to apply the solder, the Kevlar was not damaged. And, the metal-coated Kevlar "wetted" with solder quite readily. When standard electrical solder was used, the same results were obtained. Further, the metal-coated Kevlar could be soldered not only to itself, but also to other metal.

The installation of crimped connectors was attempted next. First, the insulation (if present) must be stripped back to expose the metal-coated Kevlar. As was discussed earlier,

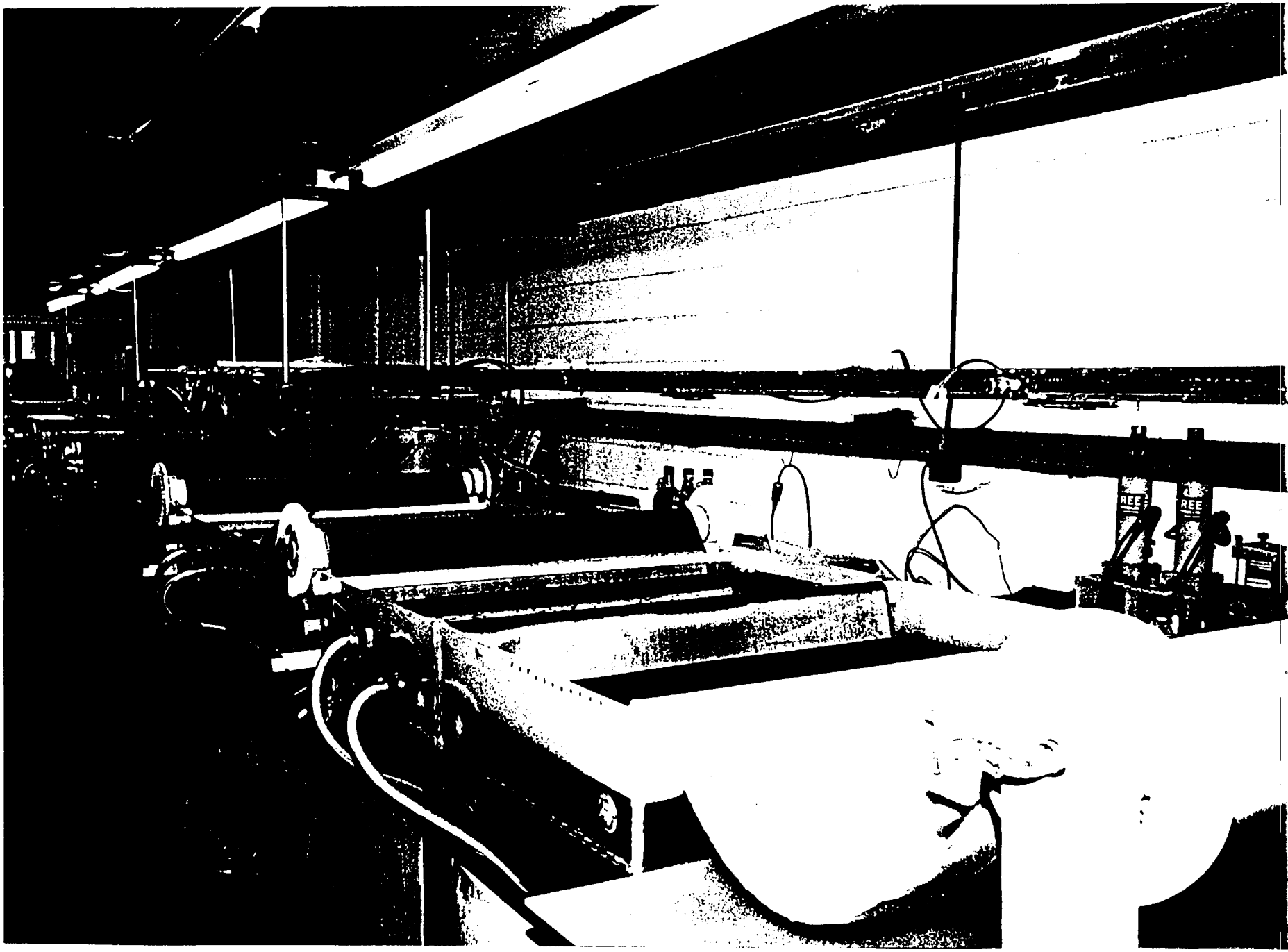


FIGURE 12. BEGINNING OF PROCESSING OF WIDE FABRIC

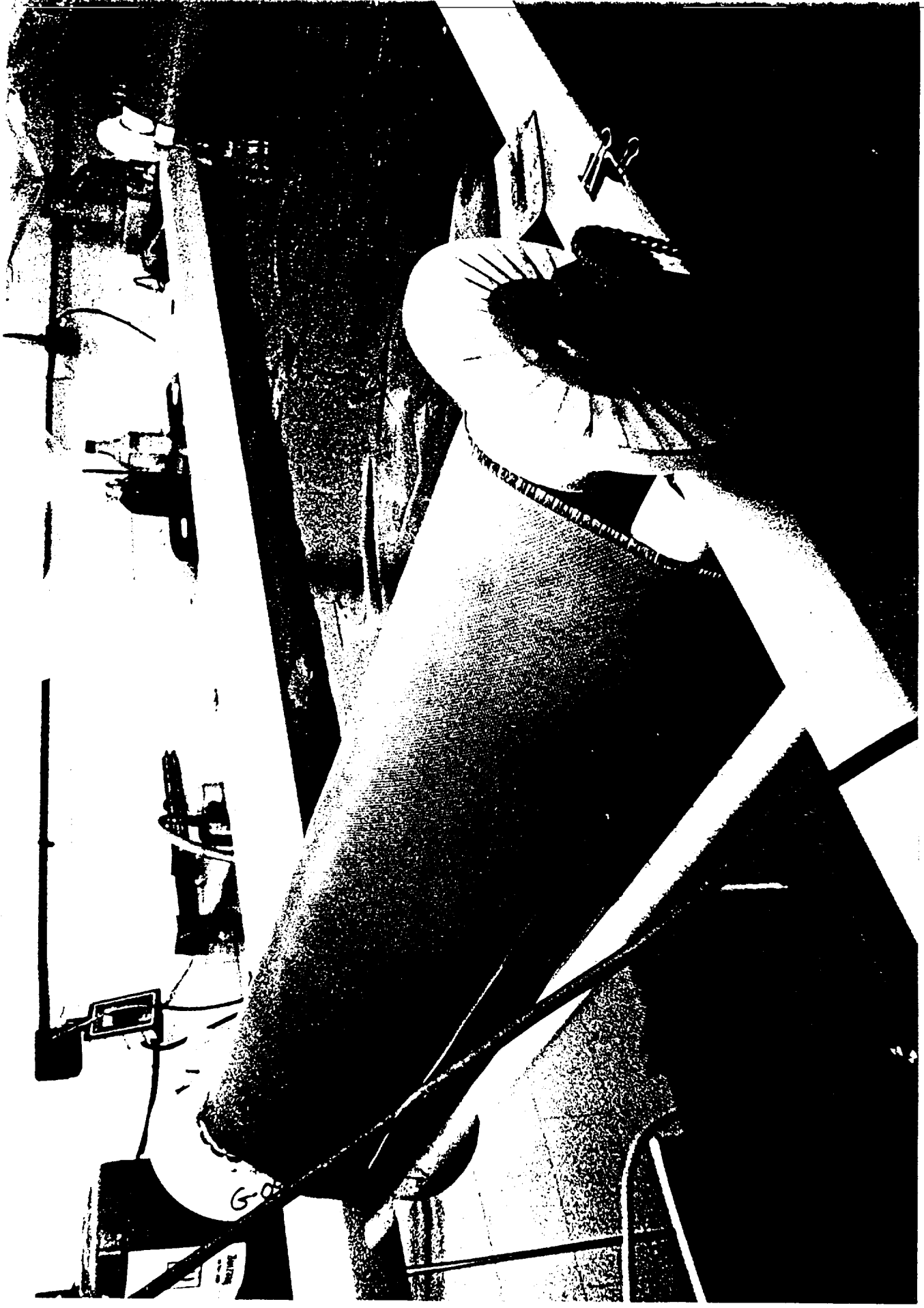


FIGURE 13. COPPER COATING OF WIDE FABRIC

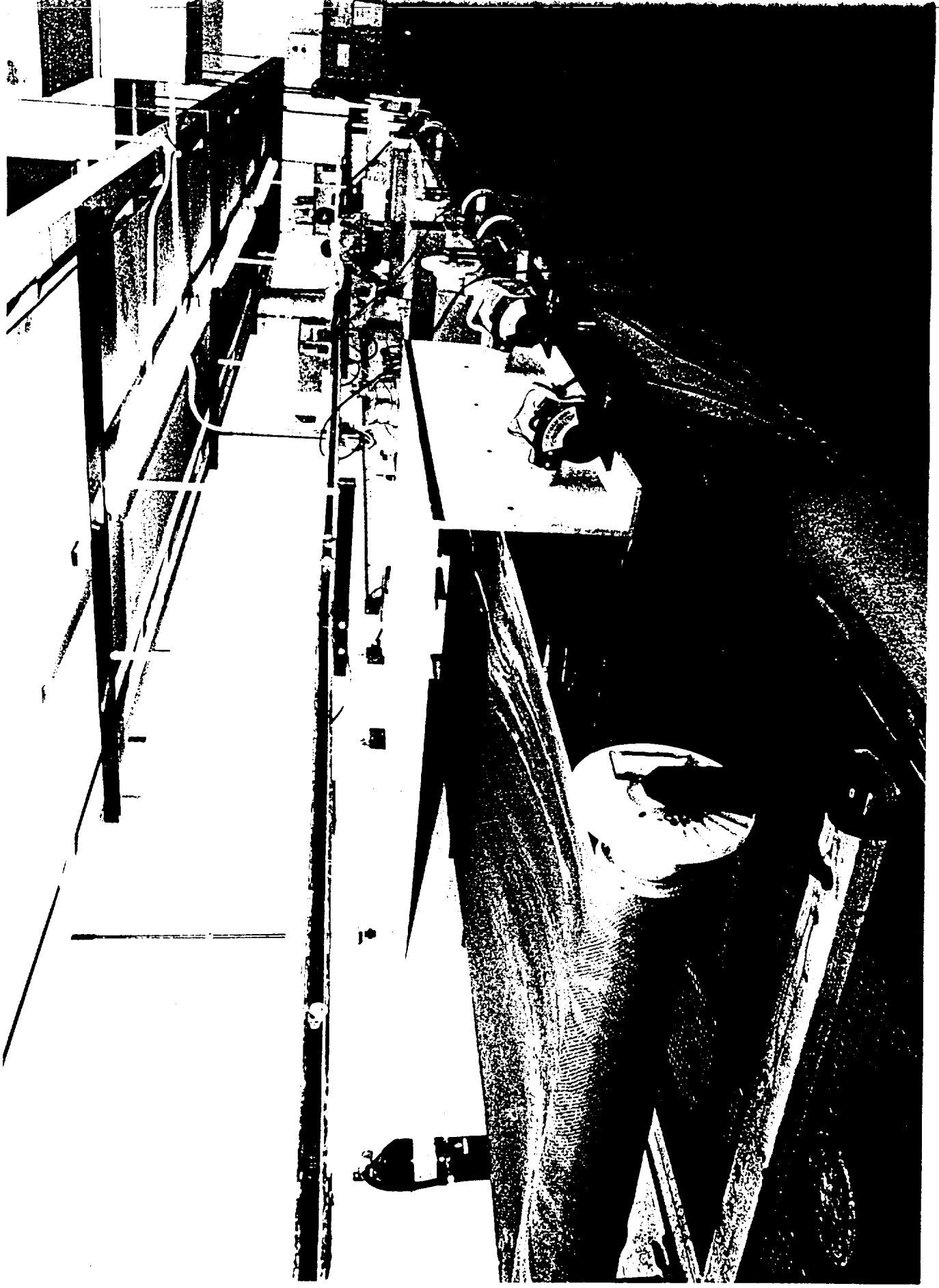


FIGURE 14. FINISHED METAL-COATED WIDE FABRIC

stripping of the tubing extruded Teflon prototypes was easily done, but the pressure extruded prototype could not be stripped without damaging some of the fibers. Crimped connectors were then installed on Teflon coated prototype samples. Both soldered and crimped electrical terminations are shown in Figure 15.

CONCLUSIONS

Several conclusions can be drawn from the subject program:

1. Kevlar (polyaramid) can be successfully metal coated for a space tether system.

2. When assembling a space tether, electrical resistances can become quite attractive (i.e., low), especially when using several multifilament tows in a tether construction.

3. Kevlar fiber is not degraded by the metal-coating process, and polymeric insulators can be applied without any complications.

4. Metal-coated Kevlar can be woven and braided without any special handling procedures, and metal coating improves the self-abrasion characteristics of Kevlar.

5. Metal coating, polymeric coating, and use of an outer jacket of metal-coated Kevlar all offer a degree of protection against atomic oxygen.

6. Control of the metal-coating process and quality of the coating can be maintained with the proper equipment.

7. Continuous processing is preferred over batch processing at this time.

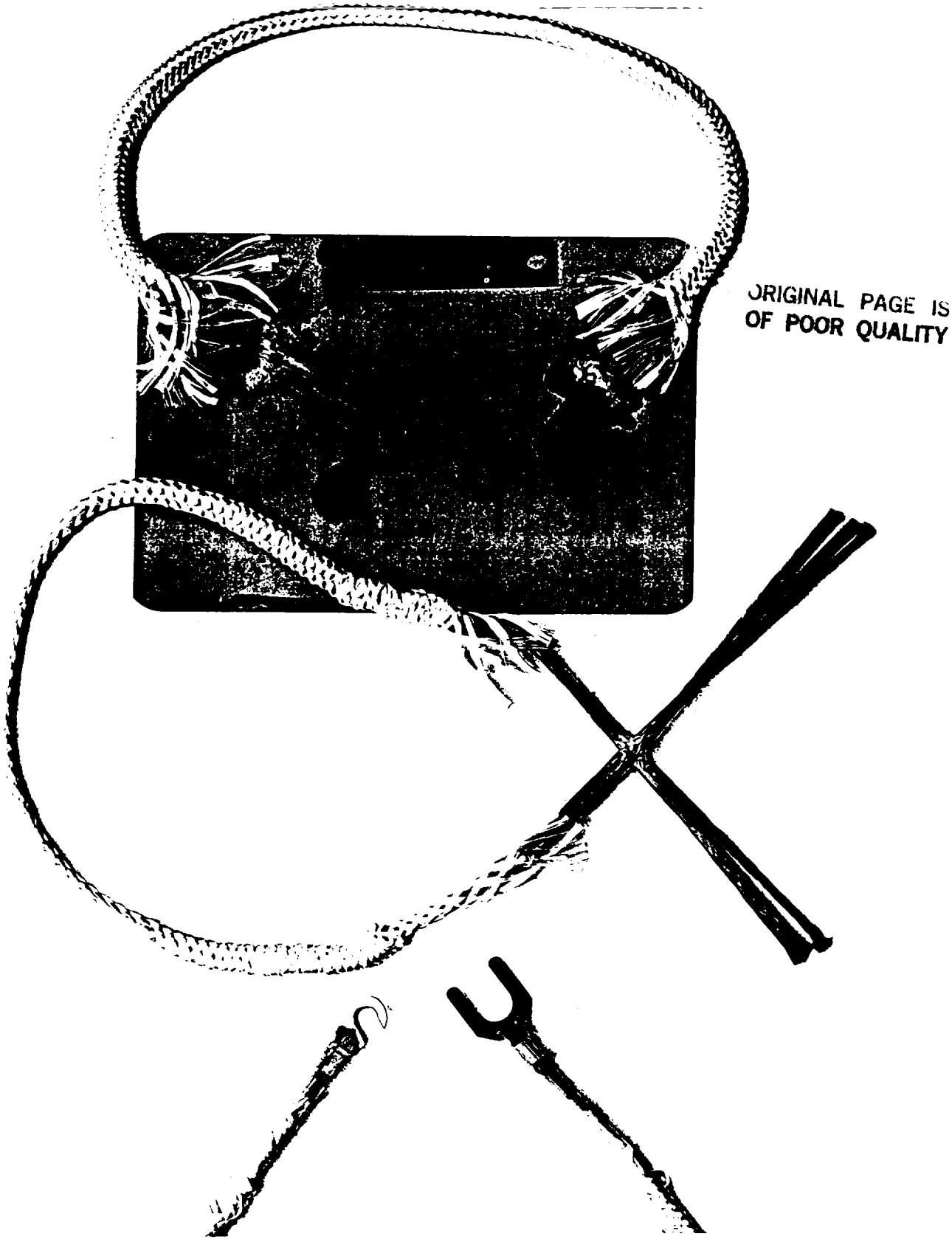


FIGURE 15. SOLDERED AND CRIMPED ELECTRICAL TERMINATIONS

8. Preliminary damping studies of metal-coated Kevlar have produced favorable results.

9. Metal-coated Kevlar in a tether or cable configuration can be electrically terminated by both soldering and crimping.

10. Wide fabric can be metal coated similarly to multifilament fiber with the proper equipment.

RECOMMENDATIONS

It is recommended that the following points be addressed in future work on metal-coated fiber systems for space tether use:

1. The processing of metal-coated fiber should be further refined, and a unit should be built to process multiple lines of fiber.

2. Other fiber systems should be investigated in addition to Kevlar, especially for high-temperature applications (e.g., quartz, fiber FP, and silicon carbide).

3. Other metal coatings should be investigated to improve electrical conductivity (e.g., gold only, not gold over a base metal).

4. Further damping studies should be conducted on large scale prototype tethers (i.e., multiple tow, jacketed constructions).

5. Actual space exposures should be performed to ascertain effects of atomic oxygen on metal-coated fibers.

6. Other polymeric systems should be investigated as insulators for metal-coated tether systems.

APPENDIX A

MCI QCP-2 Yarn Test Procedure

YARN TEST PROCEDURE

1.0 Scope

This procedure describes the method to be used to determine the acceptability of high strength, high modulus, continuous length fiber. This procedure describes the testing that shall be performed on all fiber lots prior to release of the fiber for production of continuously reinforced metal matrix composite precursor wire.

2.0 Applicable Material

This procedure is applicable to the testing of fibers derived from PAN or pitch precursor.

3.0 Applicable Documents

MCI-QCP-1	Operation of the Instron Universal Testing Machine
MCI-QCP-3	Wire Test Procedure

4.0 Test Equipment

4.1 The following test equipment is required to perform the testing described in this procedure.

a) Instron Universal Testing Instrument,Model TM-S 1102
b) Instron Load Cell, Model LS11-301, 1000 lb. capacity
c) Instron Upper and Lower Air Grips, Model 3C, 200 lb. capacity
d) Ohaus Model B300D or equivalent balance capable of .001 gram resolution with 10 gram or greater capacity
e) Two inch wide 400 grit emery cloth
f) Tensile modulus test fixture,constantan wire, solder, soldering iron, vise clips, insulating labels
g) Union Carbide "Bakelite" epoxy resin No. ERL-4221
h) Harshaw Chemical Company boron fluoride monoethylamine complex No. BF3-400
i) acetone
j) single sided adhesive cellophane tape
k) yarn fiber stringup fixture
l) industrial oven(s) with 125-500 degree celsius capability
m) 400 milliliter pyrex beaker
n) plastic spatula
o) 30 milliliter syringes or 3 milliliter dropper
p) aluminum foil
q) diagonal cutters
r) latex surgical gloves

s) surgical mask
t) fiber twist fixture, flag, ceramic insulator
u) Strain Indicator

5.0 Procedure for the Preparation of Test Specimens

5.1 Obtain fiber from inventory for acceptance testing.

5.2 In order to tensile test and modulus test the fiber, the fiber samples must be impregnated with an epoxy.

5.2.1 Dissolve one part by weight boron fluoride fluoride monoethylamine complex in one part by weight acetone. Use the 400 ml pyrex beaker.

5.2.2 Add thirty parts by weight epoxy resin to solution prepared in 5.2.1. Stir well.

5.2.3 The final solution should not be used until the solution temperature reaches 20 degrees celsius. The final solution may be preserved by covering and refrigerating at 5 degrees celsius.

5.2.4 A solution mixture of 5 grams:5 grams:150 grams provides enough resin to impregnate up to (8) ten feet fiber samples.

5.3 Get the yarn fiber stringup fixture. Clean residue from the fixture. Wrap aluminum foil around the horizontal tubular parts of the fixture. Secure the foil to the fixture using cellophane tape.

5.4 Using latex surgical gloves remove (3) ten feet lengths and (1) five feet length from each roll of fiber to be tested. Exercise care not to damage the fiber. Identify each sample to permit correlation of test results with fiber roll identification number.

5.5 The Yarn Test Form, Attachment 1, should be used to maintain fiber identification and test results.

6.0 Linear Density and Sizing Level Determination

6.1 Weigh (2) of the fiber ten feet lengths to the nearest .001 grams. Place the (2) lengths of fiber into an oven at a temperature of 500 degrees celsius. (Reference figure 1)

6.2 Remove the (2) lengths of fiber from the oven after (30) minutes. Immediately weight each length to the nearest .001 grams.

6.3 Record the weights on the Yarn Test Form.

7.0 Fiber Twist Determination

7.1 Obtain the fiber twist fixture. Using approximately (2) feet of fiber from the (5) feet sample length, secure one end of the fiber to the fixture using cellophane tape. Thread the ceramic insulator over the free end of the fiber. Secure the free end of the fiber to the fixture using cellophane tape. Apply tension to keep the fiber taut.

7.2 Position the ceramic insulator at one end of the fiber sample. Locate the midpoint of the fiber and slide the wire flag between the fiber strands. Position the wire flag immediately forward of the insulator. (Reference figure 2)

7.3 Push the insulator to the opposite end of the fixture. Count the revolutions made by the wire flag.

7.4 Record the revolutions on the Yarn Test Form.

8.0 Tensile Strength Determination

8.1 Get the yarn fiber stringup fixture. Using (1) ten feet length of fiber wind the fiber around the fixture. Maintain approximately 1/4" spacing between wraps. Apply tension to keep the fiber taut. Do not overtension.

8.2 Secure the fiber to the stringup fixture with cellophane tape.

8.3 Position the fixture over a pan or aluminum foil.

8.4 Using the disposable syringe or the dropper, apply resin solution to each length of fiber on the stringup fixture. Apply the resin to the top of each fiber length. Apply sufficient resin to impregnate the full fiber length. (Reference figure 3)

8.5 Place the stringup fixture with impregnated fibers into the oven. Set the oven thermostatic control to 125 degrees celsius. The oven should reach this temperature over a 30 minute period. Soak the fixture and fiber at 125 degrees celsius for 15 minutes. Remove the fixture from the oven and let cool for 10 minutes. (Reference figure 4)

8.6 Using diagonal cutters, remove the samples from the fixture. Cut the samples to obtain approximately a (7) inch impregnated length of fiber. Maintain sample identification.

8.7 Select straight, fully impregnated fibers for testing. A minimum of (7) samples per fiber roll is required. Four (4) samples minimum are required for for tensile strength determination while three (3) are required for tensile modulus determination.

8.8 Load each sample fiber length to failure using the Instron Universal Testing Instrument. Record the load in lbs. at which the fiber sample failed on the Yarn Test Form. Refer to MCI-QCP-3, Wire Test Procedure, for the proper test technique.

9.0 Tensile Modulus Determination

9.1 Tensile modulus testing is not performed on all fiber rolls. Contact the quality control engineer to determine the sampling plan to be used for each lot to be tested.

9.2 Get the tensile modulus test fixture.

9.3 Position the two insulated labels on the impregnated fiber in accordance with figure 5.

9.4 Position the vise clip on the label (two places). The 5" length dimension between between vise clips, inner edge to inner edge, must be maintained to +1/32",-0". Lay the fiber/label/clip configuration in the tensile modulus fixture for attachment of the constantan strain gage wire. (Reference figure 6)

9.5 Position the wire over the clips as shown in figures 5,6. Apply rosin flux to the clip. Solder the constantan wire to the clip using a 60/40 or 63/37 rosin core solder and a 25 watt soldering iron.

9.6 Remove the sample from the tensile modulus fixture. Inspect the constantan strain gage wire. Verify that the strain gage wire is securely bonded to the vise clip with solder. Verify that the strain gage wire is in tension. This may be performed visually and then verified through the use of the strain indicator.

9.7 Position the sample in the jaws of the Instron Universal Testing Instrument. Attach leads from the

strain indicator "Measuring Gage" terminals to the strain gage wire. (Reference figures 7,8) Manufacturer's instructions for the use of the strain indicator are filed in the quality control inspection area.

9.8 A dummy gage is required for attachment to the "Compensation Gage"terminals. The dummy gage is prepared in the same fashion as the sample gage except the constantan wire length of the dummy gage is required to be .001"-.015" less than the sample gage length.

9.9 Load the sample from 10 lbs to 50 lbs in 10 lbs increments. Record the load/strain readings at each load increment on the Yarn Test Form.

10.0 Fiber Roll Trial Infiltration Testing

10.1 An approximate (200) feet length of fiber from every fiber roll is to be converted to metal matrix precursor wire. The matrix material used for trial infiltration shall be aluminum alloy 6061 unless otherwise indicated by contract or the quality control manager.

10.2 Remove a minimum of (2) four feet precursor wire lengths for fiber volume determination and tensile strength determination. The test is to be performed per MCI-QCP-3, Wire Test Procedure.

10.3 Record the results on the Yarn Test Form.

11.0 Data Processing

11.1 Load program, Yarn Test, into the HP86B Personal Computer. Input the data recorded on the Yarn Test Form. The data is to be input in the sequence requested by the program prompts.

11.2 Sample output obtained from program, Yarn Test, is included as Attachment 2. Verify the accuracy of the data inputs on the output. Sign and date the output. Forward the output to the quality control engineer for comparison of the test data output to fiber specification requirements.

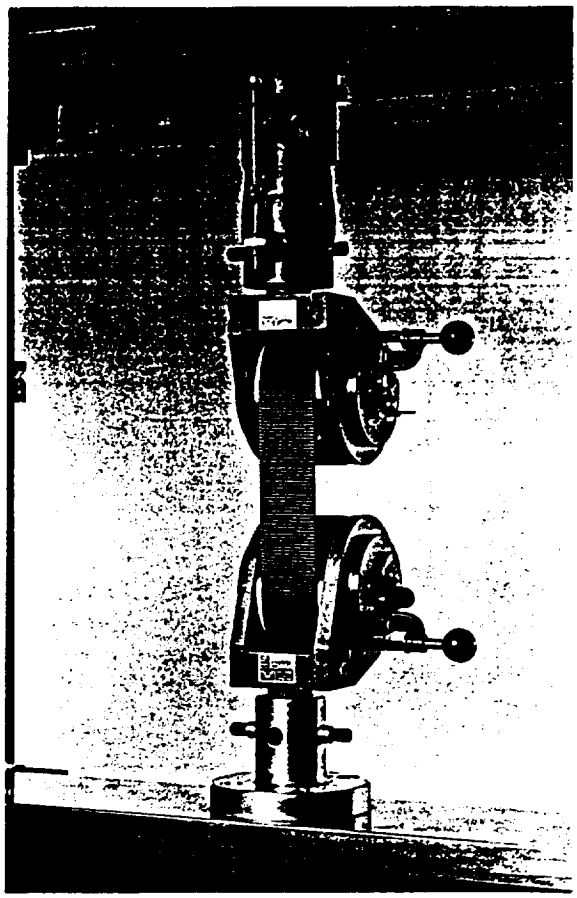
APPENDIX B

ASTM D2256-80

BREAKING LOAD AND ELONGATION OF YARN BY THE SINGLE-STRAND METHOD

AND

INSTRON CORD CAPSTAN GRIPS



Webbing Capstan Grips

Specifications

Catalog No.	2715-001	2715-003
Type	Cord Capstan	Webbing Capstan
Load Capacity	500 lb. (250 kg)	10,000 lb. (5,000 kg)
Max. Sample Dimensions	⅛ in (3 mm) dia.	2 in. (50 mm) wide x 3/16 in. (4.7mm) thick
Temperature Range	−100 to + 600° F (−73 to +315° C)	−20 to + 250°F (−30 to +120°C)
Required Sample Length	N/A	50 in (1270 mm) with 1 in (25 mm) grip separation, one inch additional for each additional inch of grip separation

INSTRON

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IC-3-86(A)

Printed in U.S.A.

Capstan Grips

INSTRON

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Cord Capstan Grips
Instron cord capstan grips are specifically designed for testing twisted or braided cord. These grips have a right hand, round groove to accommodate samples up to ⅛ inch in diameter. The design allows the sample to be loaded from the outside and wound into the center line on the upper grip. On the lower grip, the sample is wound before final gripping between the split halves of the capstan.

The capstans are 2 inches in diameter and have 2½ threads per grip. This allows two full turns of the capstan to distribute the load of heavier cords over a larger area and minimizes stress concentration at the bite.

Smooth capstan surfaces can be provided on special order (Catalog No. 2715-002) in place of the grooved surfaces to accommodate narrow tapes and belting.

Webbing Capstan Grips
These webbing capstan grips incorporate an ingenious double capstan design which provides for fast, easy loading together with a gripping action that results in proper breaks in the full gage length of the specimen. A split capstan has been arranged so that it can be rotated within a completely separate outer capstan. A sample is loaded simply by inserting an end into the groove of the inner capstan, cranking through 360° and then bringing the end out over the main capstan. Gripping efficiency is greatly increased because the surfaces of two capstans are utilized before going to the bite. The fact that the operator is able to predetermine specimen length needed for efficient routine testing is an added convenience.

These grips offer positive relief from the awkward, time-consuming capstan loading and recurring jaw breaks that are usually associated with the testing of seat belts and other high strength belts and tapes.

Continued on reverse side

Designation: D 2256 – 80

An American National Standard

Standard Test Method for BREAKING LOAD (STRENGTH) AND ELONGATION OF YARN BY THE SINGLE-STRAND METHOD[1]

This standard is issued under the fixed designation D 2256; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of reapproval.

1. Scope

1.1 This method covers the determination of breaking load and elongation of monofilament, multifilament, and spun yarns, either single, plied, or cabled with the exception of yarns that stretch more than 5.0 % when tension is increased from 0.5 to 1.0 gf/tex (5 to 10 mN/tex).

1.2 Options are included for the testing of (*1*) conditioned, (*2*) wet, and (*3*) oven-dried specimens.

1.3 Options are included for the testing of specimens in (*A*) straight, (*B*) knotted, and (*C*) looped form.

NOTE 1—Special methods for testing yarns made from specific fibers (namely, asbestos, glass, flax, hemp, ramie, and kraft paper and for specific products, namely tire cords and rope), have been published: Methods D 885, Specification D 299, for Asbestos Yarns,[2] Specification D 578, for Glass Yarns,[3] and Method D 2653, Test for Breaking Load and Elongation of Elastomeric Yarns (Constant-Rate-of-Extension Instruments).[2]

NOTE 2—For directions covering the determination of yarn strength by the skein method refer to Method D 1578, Test for Breaking Load (Strength) of Yarn (Skein Method).[2]

2. Applicable Documents

2.1 *ASTM Standards*:

D 76 Specification for Tensile Testing Machines for Textiles[2, 3]

D 123 Definitions of Terms Relating to Textiles[2, 3]

D 885 Testing Tire Cords, Tire Cord Fabrics, and Industrial Filament Yarns Made from Organic-Base Fibers[2]

D 1906 Test for Estimation of Effective Gage Length by Evaluation of Clamp Error in Single Fiber Testing[4]

D 2101 Test for Tensile Properties of Single Man-Made Fibers Taken from Yarns and Tows[5]

D 2258 Practice for Sampling Yarn for Testing[2]

3. Definitions

3.1 *breaking load*, *n*—the maximum load (or force) applied to a specimen in a tension test carried to rupture.

3.2 *elongation*, *n*—increase in length; extension; increase in length of a specimen during a tension test expressed in units of length, for example, centimetres, inches, etc.

3.3 *elongation at break*, *n*—the elongation corresponding to the breaking load, that is, the maximum load.

3.4 *elongation at rupture*, *n*—the elongation corresponding to the rupture of the last component of the specimen. The elongation at rupture is usually equal to the elongation at the breaking load but may be greater. See 3.3.

3.5 *elongation, percent*, *n*—the increase in length of a specimen expressed as a percentage of the original length.

[1] This method is under the jurisdiction of ASTM Committee D-13 on Textiles, and is the direct responsibility of Subcommittee D13.58 on Yarn Test Methods, General.

Current edition approved Sept. 2, 1980. Published November 1980. Originally published as D 2256 – 64 T. Last previous edition D 2256 – 75.

[2] *Annual Book of ASTM Standards*, Part 32.

[3] *Annual Book of ASTM Standards*, Part 33.

[4] Discontinued, see *1976 Book of ASTM Standards*, Part 25.

[5] Tweedie, A. S., Metton, M. T., and Fry, J. M., *Textile Research Journal*, TRJOA, Vol 29, March 1959, pp. 2[illegible] and Tweedie, A. S., and Metton, M. T., *Textile Research Journal*, TRJOA, Vol 29, July 1959, pp. 589–591.

3.6 *initial modulus*, *n*—the s[illegible] straight portion of a stress – [illegible] elongation) curve.

3.6.1 The modulus is the ra[illegible] in stress, expressed in grams-[illegible] (gf/den.) or grams-force per [illegible] millinewtons per tex (mN/te[illegible] in strain, expressed as a fracti[illegible] length.

3.6.2 When stress is expre[illegible] and strain as percent elongatio[illegible] line portion of the load – elo[illegible] is convenient to calculate the[illegible] using the following equation:

Initial Modulus = (tenacity/percen[illegible]

3.7 *knot-breaking strength*, [illegible] strength of a strand with a [illegible] portion of the specimen betw[illegible]

3.8 *loop-breaking strength*, [illegible] strength of a specimen consist[illegible] of yarn or monofilament fror[illegible] age looped together so that or[illegible] its ends in one clamp of the[illegible] and the other length has bo[illegible] other clamp.

3.9 *single-strand strength*, [illegible] strength of a single strand o[illegible] ment or cord, not knotted or [illegible] ning straight between the cla[illegible] machine.

3.10 *tenacity*, *n*—the tensil[illegible] as force per unit linear density [illegible] specimen.

3.10.1 Tenacity is commo[illegible] grams-force per tex (gf/tex), [illegible] denier (gf/den.), millinewto[illegible] tex), or millinewtons per d[illegible] Millinewtons are numerically [illegible] force times 9.81.

3.11 *tenacity, breaking n*— [illegible] responding to the breaking lo[illegible]

3.11.1 Breaking tenacity i[illegible] pressed as grams-force per te[illegible] force per denier (gf/den.), mi[illegible] mN/tex), or millinewtons [illegible] den.). Millinewtons are num[illegible] grams-force times 9.81.

3.12 For definitions of o[illegible] used in this method, refer to I[illegible]

4. Summary of Method

4.1 A specimen is placed i[illegible]

3.6 *initial modulus, n*—the slope of the initial straight portion of a stress – strain (or load – elongation) curve.

3.6.1 The modulus is the ratio of the change in stress, expressed in grams-force per denier (gf/den.) or grams-force per tex (gf/tex), or millinewtons per tex (mN/tex), to the change in strain, expressed as a fraction of the original length.

3.6.2 When stress is expressed as tenacity and strain as percent elongation, for the straight line portion of the load – elongation curve, it is convenient to calculate the initial modulus using the following equation:

Initial Modulus
= (tenacity/percent elongation) × 100

3.7 *knot-breaking strength, n*—the breaking strength of a strand with a knot tied in the portion of the specimen between the clamps

3.8 *loop-breaking strength, n*—the breaking strength of a specimen consisting of two lengths of yarn or monofilament from the same package looped together so that one length has both its ends in one clamp of the testing machine and the other length has both its ends in the other clamp.

3.9 *single-strand strength, n*—the breaking strength of a single strand of yarn, monofilament or cord, not knotted or looped but running straight between the clamps of the testing machine.

3.10 *tenacity, n*—the tensile stress expressed as force per unit linear density of the unstrained specimen.

3.10.1 Tenacity is commonly expressed as grams-force per tex (gf/tex), grams-force per denier (gf/den.), millinewtons per tex (mN/tex), or millinewtons per denier (mN/den.) Millinewtons are numerically equal to grams-force times 9.81.

3.11 *tenacity, breaking n*—the tenacity corresponding to the breaking load.

3.11.1 Breaking tenacity is commonly expressed as grams-force per tex (gf/tex), grams-force per denier (gf/den.), millinewtons per tex (mN/tex), or millinewtons per denier (mN/den.). Millinewtons are numerically equal to grams-force times 9.81.

3.12 For definitions of other textile terms used in this method, refer to Definitions D 123.

4. Summary of Method

4.1 A specimen is placed in the clamps of a tensile testing machine, stretched or loaded until broken, and the breaking load and elongation observed. Elongation at a specified load or the load or tenacity at a specified elongation may also be obtained.

4.2 This method offers three options with respect to moisture content of the specimens at the time of testing:

4.2.1 *Option 1*, conditioned (in moisture equilibrium for testing with the standard atmosphere for testing textiles).

4.2.2 *Option 2*, wet.

4.2.3 *Option 3*, oven-dry.

4.3 The method also offers three options for the physical conformation of the specimen:

4.3.1 *Option A*, straight.

4.3.2 *Option B*, knotted.

4.3.3 *Option C*, looped.

4.4 Unless otherwise indicated, the phrase "single-strand strength" is assumed to refer to a straight, conditioned specimen (Option 1A).

5. Uses and Significance

5.1 Method D 2256 is considered satisfactory for acceptance testing of commercial shipments since the methods have been used extensively in the trade for acceptance testing. However, this is not applicable to knot and loop strength tests, tests on wet specimens, or tests on oven-dry specimens. In cases of disagreement arising from differences in values reported by the purchaser and the seller when using this method for acceptance testing, the statistical bias, if any, between the laboratory of the purchaser and the laboratory of the seller should be determined with each comparison based on testing specimens randomly drawn from one sample of material of the type being evaluated.

5.2 The procedures in this method should be used with caution for acceptance testing because factual information on between-laboratory precision is not available. It is recommended that any program of acceptance testing be preceded by an interlaboratory check in the laboratories of the purchaser and seller on randomized replicate specimens of materials similar to those being evaluated.

5.3 *Strength*:

5.3.1 The strength of a yarn influences the strength of fabrics made from the yarn, although the strength of a fabric also depends on its construction and may be affected by finish-

ing operations.

5.3.2 Since for any fiber type bre ing load is approximately proportional to line r density, strands of different sizes can be compared by converting the observed breaking load to breaking tenacity (grams-force per tex or grams-force per denier (millinewtons per tex)).

5.3.3 The single-strand method gives a more accurate measure of strength and elongation and more information on the amount of variation present in the material than does the skein method. On the other hand, the single-strand method, while using less material, requires more of an operator's time and is accordingly more costly. The skein-breaking load is always lower than the sum of the breaking loads of the same number of ends broken individually.

5.4 *Elongation*:

5.4.1 Elongation is an indication of the ability of a yarn or fabric to absorb energy. If the elongation at break of warp yarns is too low, weaving becomes difficult or even impossible. On the other hand, low-elongation yarns (and fabrics made from them) have greater dimensional stability. Garments made from such yarns are less likely to become "baggy" at the knees, elbows, or other points of stress. Low-elongation yarns or cords are also desirable as reinforcement for plastic products, hose, tires, etc.

5.4.2 Since observed elongation varies directly with the nominal gage length of the specimen, the observed values are usually converted to percent elongation for comparative purposes.

5.4.3 Yarns made from blends or combinations of fibers may show elongation beyond the point of maximum load, particularly if one of the components is an elastomeric fiber. When the low elongation components of a yarn are broken, the load falls on the remaining fibers, which continue to elongate until they, in turn, are broken. Breaking elongation is defined as that corresponding to the maximum load. If elongation continues after the maximum load has been passed, then elongation at rupture may be determined separately.

5.5 *Load-Elongation Curves*:

5.5.1 Load-elongation curves permit the calculation of various values, not all of which are discussed in this method, such as elongation at break, elongation at specified load, load at specified elongation, initial elastic modulus (resistance to stretching), compliance (ability yield under stress), which is the reciprocal the elastic modulus, and area under the which is proportional to the work done and a measure of "toughness." The calculation toughness is included in the Method D 2101

NOTE 3—Load-elongation curves can be verted to stress-strain curves if the load is con to unit stress, that is, to grams-force per tex or g force per denier (millinewtons per tex), or pound square inch (pascals) and the elongation is base change per unit length (such as percent).

5.6 *Knot and Loop Strength*:

5.6.1 The reduction in strength due presence of a knot or loop is considered measure of the brittleness of the yarn. El tion in knot or loop tests is not known to any significance and is not usually recorded

5.7 *Rate of Operation*:

5.7.1 The breaking load decreases slightly time-to-break increases. The rate of change believed to be of the order of magnitude of to 10 % decrease in the breaking load for tenfold increase in the time-to-break.

5.7.2 Operation of CRT, CRE, and CRL machines at a constant time-to-break has been found to minimize differences in test results between the three types of testing machines. When all tests are performed at a fixed time-to-break, then good agreement has been found to exist between CRT and CRE testers. Consistent results are also obtained between CRL testers when they are operated at the same time-to-break. The agreement is not necessarily good, however, between CRE or CRT testers on the one hand and CRL testers on the other even when they are all operated at the same time-to-break.

5.7.3 This method specifies an average time-to-break of 20 ± 3 s as recommended by ISO/TC 38 on Textiles.

5.7.4 The tolerance of ±3 s for the time-to-break is wide enough to permit convenient adjustment of the testing machine's rate of operation, and it is narrow enough to ensure good agreement between tests. The difference in breaking load between tests at 17 and 23 s will usually not exceed 1.5 % of the average value.

5.7.5 In case a testing machine is not capable of being operated at 20-s time-to-break, alternative rates of operation are included in

method. These alter
only by agreement
cerned.

5.8 *Tests on Wet*
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which show a loss
when exposed to hig
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fibers based on regei
lulose. Wet tests are
detect adulteration b

5.9 *Tests on Oven-*
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specimens at standard
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testing oven-dry yar
tures.

6. Apparatus and Re

6.1 *Tensile Testing*
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should be no greater
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and used to test specir
water is a necessary ac
loading and recording
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requirements as to gag
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NOTE 4—Flat-faced cl
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to the jaws exceeds statisti
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machine to break the spec

ward a whole number when n is less than 50 or to a multiple of five when n is 50 or more),

v = reliable estimate of the coefficient of variation of individual observations on similar material in the user's laboratory under conditions of single-operator precision.

t = 1.645, the value of Student's t for infinite degrees of freedom, for one-sided limits, and a 95 % probability level ($t^2 = 2.706$),

A = values of the allowable variations listed in Table 1, and

t^2/A^2 = basis for calculation of the constants in the equation in Table 1.

7.3.1.2 *No Reliable Estimate of v*—When there is no reliable estimate of v for the user's laboratory, Eq 1 should not be used directly. Instead, specify the fixed numbers of specimens shown in Table 1. These numbers of specimens are calculated using values of v that are listed in Table 1 and which are somewhat larger values of v than are usually found in practice. When a reliable estimate of v for the user's laboratory becomes available, the equations in Table 1, which are based on Eq 1, will usually require fewer specimens than are listed in Table 1 for the condition when there is no reliable estimate of v.

7.3.2 For filament yarns, test one specimen per package (or per end, if the material is put up in packages containing two or more ends wound parallel); for spun plied yarns, two specimens per package or per end; and for spun single yarn, five specimens per package or per end, from enough packages to give the required number of specimens. In Option C, each specimen consists of two pieces of yarn, both taken from the same end.

8. Conditioning and Preparation of Specimens

8.1 *Option 1, Conditioned Specimens*—Reel a short skein from each of the packages forming the laboratory sample. Precondition the skeins by bringing the material into approximate moisture equilibrium with an atmosphere having a relative humidity between 5 and 25 % at a temperature no higher than 120°F (50°C). After preconditioning, bring the sample skeins to moisture equilibrium for testing in the standard atmosphere for testing textiles. Equilibrium is considered to have been reached when two successive weighings not less than 15 min apart do not differ by more than 0.1 % of the weight of the yarn.

NOTE 5—Conditioning in skein form is much more rapid than conditioning of tightly wound packages and is needed whenever other tests are also made on the same sample, that is, tests requiring a large amount of conditioned material. However, the outer layers of a tight package reach approximate equilibrium in a reasonable length of time; and when only a few yards are to be used and extreme accuracy is not required (as, for example, in production control work) it may be more convenient to condition the yarn in package form.

8.2 *Option 2, Wet Specimens*—Without disturbing twist, place the specimen on a holder and submerge in distilled water at room temperature until thoroughly soaked. The time of immersion must be sufficient to wet out the specimens thoroughly, as indicated by no significant further change in strength or elongation following longer periods of immersion. This time period will be at least 2 min for regenerated cellulose yarns and at least 10 min for acetate. For yarns not readily wet out with water, such as those treated with water-repellent or water-resistant materials, add a 0.1 % solution of a nonionic wetting agent to the water bath. Do not use any agent that will affect the physical properties of the yarn appreciably.

8.3 *Option 3, Oven-Dry Specimens*—Oven-dry the specimens as directed in Section 22 of Methods D 885.

8.4 When using Option 2B or Option 3B, tie the knots very loosely before wetting or drying the specimens, in order to save time and to avoid handling while transferring the specimens from the container to the testing machine.

9. Procedure

9.1 *Rate of Operation of Testing Machine*

9.1.1 *Preferred Rate*—Operate all machines at a rate to reach the breaking load in an average time of 20 ± 3 s from the start of the test. Break one or more trial specimens, observe the time-to-break, and adjust the rate of loading if necessary.

9.1.2 *Alternative Rates*—In case the testing machine is not capable of operating as specified in 9.1.1, select a rate that will reach the breaking load in an average time as close to 20 s as possible and report the average time to break. For CRL machines, the rate of loading

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9.4 *Option*

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or grams-force per denier (millinewtons per tex) (average load divided by average direct yarn number).

10.2 *Elongation (Option A, only)*—Read the elongation at break, or at the specified load, from the load-elongation chart (or elongation at break from an elongation-indicating device on the machine). Calculate the percent elongation on the basis of the nominal gage length.

NOTE 7—The length of the yarn actually stretched is usually somewhat greater than the nominal gage length. See the definitions of *Gage Length, Effective*; *Gage Length, Nominal*; and *Gage Length, True* in Definitions D 123 and Method D 1906.

10.3 *Initial Modulus*—On the stress-strain curve, draw a line extending the initial straight-line portion of the curve downward to the zero-load axis and upward beyond the point representing 10 % elongation. From the intersection with the base line, mark off a distance equal to 10 % elongation and erect a perpendicular from this point to the point where it intersects the sloping line. This intersection represents the stress required to elongate the specimen 10 %. Calculate the initial modulus by Eq 2:

$$\text{Initial modulus, gf/tex (or gf/den (or mN/tex))} = \frac{10 \times \text{load, gf(mN) for 10 \% elongation}}{\text{yarn number in tex or denier}} \quad (2)$$

11. Report

11.1 State that the tests were made in accordance with ASTM Method D 2256. Describe the material(s) or product(s) tested and the method of sampling used.

11.2 Report the following information concerning conditions of test:

11.2.1 Method of conditioning package or skein,

11.2.2 Option used,

11.2.3 Number of specimens tested,

11.2.4 Average and coefficient of variation of breaking load,

11.2.5 Average breaking tenacity,

11.2.6 Average and coefficient of variation of percent elongation at break or at specified load if determined,

11.2.7 Average load or tenacity at specified elongation, if determined,

11.2.8 Average initial modulus, if determined,

11.2.9 Number of test results rejected (slippage breaks),

11.2.10 Type of machine and capacity of machine used,

11.2.11 Rate of operation,

11.2.12 Nominal gage length,

11.2.13 Average time-to-break, and

11.2.14 Type of clamps used and jaw faces if other than flat metal.

12. Precision and Accuracy

12.1 *Interlaboratory Test Data*[6]—Factual information on interlaboratory testing of the several generic types as continuous filament and spun yarns is not available. The data in Table 2 are based on information supplied by 11 laboratories from tests made on each company's production. The calculated single-operator components of variance expressed as coefficients of variation are listed in Table 2.

12.2 *Precision*—For the components of variance reported in 12.1, two averages of observed values should be considered significantly different at the 95 % confidence level, if the difference equals or exceeds the critical differences listed in Table 3. No information on between-laboratory precision is available.

12.3 *Accuracy*—No justifiable statement can be made on the accuracy of Method D 2256 for testing for the properties listed in Table 1 and Table 2, since the true values of the properties cannot be established by accepted referee methods.

[6] Data from the within-laboratory tests can be inspected at the Technical Center, Fibers Division, Allied Chemical Corp., Petersburg, Va. 23803.

TABLE 1 Number of Specimens

Name of the Properties	
Breaking Strength:	
Continuous filament—dry	
Continuous filament—wet	
Spun yarns	
Spun cotton cords	
Cotton sewing threads	
Breaking Elongation:	
Continuous filament—dry	
Continuous filament—wet	
Spun yarns	
Cotton sewing threads	
Knot Strength:	
Continuous filament—dry	
Spun yarns	
Spun cotton cords	
Cotton sewing threads	
Loop Strength:	
Continuous filament—dry	
Spun yarns	
Spun cotton cords	
Cotton sewing threads	

[5] The values of *v* in the right hand ... 7.1.2)

TABLE 2 Single-Op...

Yarn Type	
Continuous Filament Yarns:	
Nylon, polyester, rayon, or acetate	
Rayon (wet)	
Spun Yarns:	
Rayon, cotton, acrylic, polyvinyls, wool, or cotton polyester blends	
Cotton cords	
Cotton sewing threads	

[4] No estimates are available.

TABLE 1 Number of Specimens Required Under Conditions of Known and Unknown Variability in User's Laboratory Percent of the Average

Name of the Properties	Allowable Variation (One-Sided)	Equations for n Using a Reliable Estimate of v	No Reliable Estimate of v	
			Number of Specimens	Basis[A]
Breaking Strength:				
Continuous filament—dry	3.00	$n = 0.301 \times v^2$	15	7.00
Continuous filament—wet	3.00	$n = 0.301 \times v^2$	85	16.80
Spun yarns	4.00	$n = 0.169 \times v^2$	48	16.80
Spun cotton cords	4.00	$n = 0.169 \times v^2$	9	7.00
Cotton sewing threads	4.00	$n = 0.169 \times v^2$	22	11.20
Breaking Elongation:				
Continuous filament—dry	3.00	$n = 0.301 \times v^2$	60	14.0
Continuous filament—wet	3.00	$n = 0.301 \times v^2$	38	11.2
Spun yarns	4.00	$n = 0.169 \times v^2$	48	16.8
Cotton sewing threads	4.00	$n = 0.169 \times v^2$	41	15.4
Knot Strength:				
Continuous filament—dry	3.00	$n = 0.301 \times v^2$	22	8.40
Spun yarns	4.00	$n = 0.169 \times v^2$	6	5.60
Spun cotton cords	4.00	$n = 0.169 \times v^2$	2	2.80
Cotton sewing threads	4.00	$n = 0.169 \times v^2$	41	15.40
Loop Strength:				
Continuous filament—dry	3.00	$n = 0.301 \times v^2$	15	7.00
Spun yarns	4.00	$n = 0.169 \times v^2$	17	9.80
Spun cotton cords	4.00	$n = 0.169 \times v^2$	12	8.40
Cotton sewing threads	4.00	$n = 0.169 \times v^2$	17	9.80

[A] The values of v in the right hand column of Table 1 are somewhat larger than will usually be found in practice (see 7.2).

TABLE 2 Single-Operator Components of Variance Expressed as Coefficients of Variation

Yarn Type	Breaking Strength	Breaking Elongation	Knot Strength	Loop Strength
Continuous Filament Yarns:				
Nylon, polyester, rayon, or acetate	5	10	6	5
Rayon (wet)	12	8	[A]	[A]
Spun Yarns:				
Rayon, cotton, acrylic, polyvinyls, wool, or cotton polyester blends	12	12	4	7
Cotton cords	5	[A]	2	6
Cotton sewing threads	8	11	11	7

[A] No estimates are available.

TABLE 3 Critical Differences, Percent of the Grand Average for Conditions of Single-Operator Precision[A,B]

	Number of Observations in Each Average	Breaking Strength	Breaking Elongation	Knot Strength	Loop Strength
Continuous Filament Yarns:					
Nylon, polyester, rayon, or acetate	1	13.9	27.7	16.6	
	5	6.2	12.4	7.4	
	10	4.4	8.8	5.3	
Rayon (wet)	1	33.3	22.2	...	
	5	14.9	9.9	...	
	10	10.5	7.0	...	
Spun Yarns:					
Rayon, cotton, acrylic, polyvinyls, wool, or cotton polyester blends	1	33.3	33.3	11.1	
	5	14.9	14.9	5.0	
	10	10.5	10.5	3.5	
Cotton cords	1	13.9	...	5.5	
	5	6.8	...	2.5	
	10	4.4	...	1.8	
Cotton sewing threads	1	22.2	30.5	30.5	
	5	9.9	13.6	13.6	
	10	7.0	9.6	9.6	

[A] The critical differences were calculated using $t = 1.960$, which is based on infinite degrees of freedom.

[B] To convert the tabulated values of the critical differences to units of measure, multiply the average of the two specific sets of data being compared by the critical differences expressed as decimal fractions.

APPENDIX

X1. DIRECTION OF KNOTS

X1.1 Definitions

X1.1.1 *Overhand Knot*—A simple single knot, tied in either direction.

X1.1.2 *Bight*—A bend or loop; the middle portion as distinguished from the ends. In Figs. X1 and X2, the bight lies toward the bottom of the page.

X1.1.3 *Type "O" Knot*—One in which, when the bight is below, the bight crosses *over* the right-hand end, as shown in Fig. X1(*b*).

X1.1.4 *Type "U" Knot*—One in which, when the bight is below, the bight crosses *under* the right-hand end, as shown in Fig. 2(*b*).

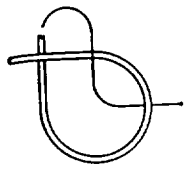
X1.2 Choice of Knots

X1.2.1 Unless otherwise agreed, use the type "O" knot for Z twist yarns and type "U" for S twist yarns. In plied yarns, the last twist determines the type of knot to be used.

X1.3 Tying Knots

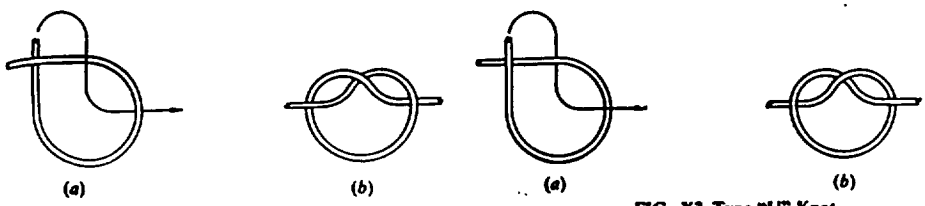
X1.3.1 To tie the type "O" knot, bend the right-hand end downward and bring it up *behind* the left-hand end, as shown in Fig. X1(*a*), then bring the right-hand end forward and pass it through the bight from front to back.

X1.3.2 To tie the type "U" knot, bend the right-hand end downward and bring it up in *front* of the left-hand end, as shown in Fig. X2(*a*); then bring the right-hand end forward through the bight from behind.



(*a*)

FIG.



(a) (b)

FIG. X1 Type "O" Knot

(a) (b)

FIG. X2 Type "U" Knot